VARIABILITY IN CLIMATIC PRODUCTIVITY OF PADDY RICE IN JAPAN

Yasuyuki SUGIHARA

Abstract The regionaliy of climatic productivity was examined from the viewpoints of seasonal variation and temperature characteristics of climatic productivity. The obtained climatic divisions are types A1 (coldest), A2 (cold), A3 (moderate), B (warm transitional), C (warm), and D (warmest). The long-range changes of climatic productivity for 6 stations representative of each agro-climatic division were obtained. The productivities of Asahikawa, Morioka, and Saga clearly indicate maximum or minimum values of climatic productivity substantially affecting the production of paddy rice. The geographical distributions of relative climatic productivity for 6 and 40 year return periods were estimated based on the changes in climatic elements for each agro-climatic division. The estimated changes in climatic productivity represent the probable deviation of the climatic productivity for the normal for the return period of 40 years.

1. Introduction

Evaluation of climatic productivity

The term climatic productivity for paddy rice represents the volume of climatic resources affecting the amount of paddy rice production (Hanyu, *et al.*, 1966).

The dry matter productivity of paddy rice produces grain yield under certain cultivation technique. Therefore, the evaluation of climatic productivity should be due to physiological knowledge, especially theory on photosynthesis in paddy rice community.

The theory studies on photosynthesis in plant communities advanced by Monsi and Saeki (1953), Saeki (1960), and Monteith (1965) presented mathematical models. Iwaki (1975) applied these mathematical models to paddy rice. Further development of the theory by taking other factors (such as, distribution of CO_2, *etc.*) into account in the models will estimate more precisely the amount of assimilation.

As pointed out by Monsi (1968), it may also be possible, however, if simplifying some terms in the model, to estimate the bio-geographical productivity from meteorological data obtained by routine observation. From this viewpoint, Chang (1968) calculated the net photosynthesis on the assumption that the respiration relative to gross photosynthesis (by Monteith, 1965) obtained from day length and solar radiation is linear to air temperature (refer to Thomas and Hill, 1937) and obtained its global distribution (Chang, 1970).

Because the measure of paddy production, however, is represented by means of grain production it cannot be regarded as simply the sum of net photosynthesis, which is the difference between gross photosynthesis and respiration. While a large total dry matter usually indicates high yield, when the distribution ratio of the dry matter in the grain is low, this low grain-straw ratio reveals a lower yield than expected. This is often caused by the excessive vegetative growth (Tanaka, 1976). Taking this account, it was determined that dry matter productivity would not be substantial concern in the present study.

Turning to evaluation of climatic productivity of paddy rice, the author applied statistical models (Murata, 1964; Hanyu, *et al.*, 1966), which express the relation between paddy rice yield and climatic factors as physiological characteristics.

Considering the physiological data on paddy rice, Murata (1964) proposed a statistical model in which the mean yield divided by the mean daily solar radiation during the period of August-September, on the assumption of a linear relation between both quantities, could be approximated by a parabolic curve with respect to the mean air temperature during the same period. The curve indicated the maximum value at an optimum temperature, 21.5°C. He defined the relational equation as the "temperature productivity index," and the product of the index and the amount of solar radiation as the "climatic productivity index."

By using the data of climatic response test, Hanyu *et al.* (1966) obtained a similar result based on the relationship between the mean air temperature (θ_R), duration of sunshine (S_R) during the ripening period (40 days after heading) and yield (Y). This study introduced a clear conception of climatic productivity in terms of "the volume of climatic resource affecting the amount of field products" and called the index obtained from the relationship the "climatic index on quantity of ripening (Y_R)." Though this conception of climatic productivity was similar to those of the "climatic production" proposed by Daigo (1949) and the "climatic fertility" by Uchijima (1964), Hanyu *et al.*'s study clearly defined climatic productivity as the amount of climatic resource expressing potential in agricultural production at a certain technical level.

Other studies available for the evaluation of climatic productivity are as follows:

1) Munakata *et al.* (1967) presented a yield prediction formula including rice body data, which was concluded by Kudo *et al.* (1973) to be useful for yield forecast in Japan.

2) Using a non-linear regression model with mean air temperatures and duration of sunshine for four main growth stages, Munakata (1976) found significant correlation ($r=0.88$) between values estimated by the model and the mean yields for 23 prefectures for an 11 year period. Although it uses only two climatic factors without regard for any other data, the practical procedure for calculation is far too complicated because of its non-linear regression equation of 16 terms.

As for progressing directions of statistical researches based on physiological knowledge of paddy rice, Murata and Kudo (1968) introduced the mean air temperature during May-June period into Murata's climatic productivity index; and Murakami *et al.* (1973) adopted accumulation of sunshine hours based on an ever-decreasing manner towards maturity. However, a few unsolved problems seem to remain regarding this study (Sugihara and Hanyu, 1980).

The present study intends to propose as it's first subject a new climatic productivity index in the form of simple combination of climatic factors throughout all growing stages of paddy rice. Sugihara and Hanyu (1980) introduced a "sink" model into the index Y_R by Hanyu *et al.* (1966). That vessel or sink of photosynthate during the ripening period is prepared before the heading period (Evans, 1976).

The evaluation of climatic productivity for paddy rice has been attained by the following equations (Sugihara and Hanyu, 1980).

$$Y_p = l_n(1+S_R/M_G)\ \{260-2.70(\theta_R-21.5)^2\} \quad (1)$$

$$\begin{aligned}
&1)\ M_H = 0.400(\theta_H-25.0)^2+10.0,\ \theta_H \leqq 25.0\\
&\quad\ M_H = 0.625(\theta_H-25.0)^2+10.0,\ 25.0<\theta_H \leqq 27.0\\
&\quad\ M_H = 0.625(\theta_H-29.0)^2+10.0,\ 27.0>\theta_H\\
&2)\ M_V = 0.278(\theta_V-21.0)^2+9.0,\ \theta_V \leqq 21.0\\
&\quad\ M_V = 0.625(\theta_V-21.0)^2+9.0,\ 21.0<\theta_V \leqq 25.0 \qquad (2)\\
&\quad\ M_V = 0.500(\theta_V-29.0)^2+11.0,\ \theta_V>25.0\\
&3)\ M_G = M_H,\ M_H \geqq M_V\\
&\quad\ M_G = M_V,\ M_H < M_V
\end{aligned}$$

where climatic factors are summarized in Table 1.

Table 1 Symbols of the meteorological elements during each growth period.

Growth Period	Mean air temperature	Total sunshine hours
Period from 50th to 36th day prior to heading	θ_V	S_V
Period from 25th to 1 st day prior to heading	θ_H	S_H
Ripening period (40 days after heading)	θ_R	S_R

The modification of the index Y_R is evaluated by comparison of the correlations of Y_p to the actual yield (Y) and that of Y_R with Y. The correlation between Y and Y_R is 0.188 (significant at 5% level,*) and the correlation between Y and Y_p is 0.247 (significant at 1% level,**). Thus, because of its inclusion of the climatic condition before heading in terms of M_G, Y_p is more useful than Y_R for evaluation purposes.

Climatic productivity of paddy rice in Japan

Uchijima and Hanyu (1967) illustrated the geographical distribution of Y_R. It is a marked pattern of distribution that the largest index appears in the Ishikari Plain. The indices of the marginal region of Hokkaido are higher than in the Kanto Plain, because the index depends only on the ripening period. The second aim is to clarify the geographical distribution of climatic productivity of paddy rice in Japan. If the regions with actual high yield correspond to those with high index, the climatic productivity index may be usuful.

The geographical distribution of maximum Y_p (Y_{po}) at the normal suitable heading period (SHP) has already been obtained (Hanyu and Sugihara, 1981). The correlation between Y_p at actual mean heading period (Y_{pm}) and Y in the 36 regions is as high as r= 0.752(**) and high productivity regions of Y more than 550kg/10a always indicate high index greater than 780.

From these results, it is thought that Y_p is possibly an index of productivity of paddy rice under given climatic conditions.

Kudo *et al.* (1970) pointed out that statistical models based on physiological knowledge obtained by Murata (1964) and Hanyu *et al.* (1966) were poorly applicable to predict the yield.

The third subject of this chapter is to examine the applicability of the climatic productivity index for yield prediction and to re-examine cultivation limit, establishment of crop season, selection of varieties, and others in actual cultivation of paddy rice in terms of the new index.

There are 8 stations at which the correlation coefficient of Y_p at the mean heading period (Y_{pm}) with regional yield (Y) are above 0.6 (**) in the 36 main paddy regions. Those cultivating varieties seem to correspond to Y_p regarding climatic characteristics. In addition, a new model for yield prediction based on Y_{pm} by introduction of parameterized θ_o (the optimum temperature of θ_R) and the technical advancement model with stagnation was formulated as follows:

$$Y_{ni}(\theta_o)= \{A_{ni}(\theta_o)t+B_{ni}(\theta_o)\}\cdot Y_{pm}(\theta_o) \quad (3)$$

This equation was valid for yield prediction in 72% of the main paddy regions (Sugihara and Hanyu, 1982).

The normal Y_{po} 500 was regarded as a limiting value according to both the northern limit and the altitudinal limit of paddy rice cultivation in Japan (Sugihara, 1981).

Subjects of this study

Uchijima (1962) already established agro-climatic division on the basis of physical conditions, water temperature and radiative dry index, of paddy rice. Here the author establishes agro-climatic divisions based on the growth characteristics of paddy rice such as suitable heading periods and the corresponding temperatures thereof.

As to the variability of agro-climatic indices, Iwakiri (1967) examined the average mean air temperature during the period July to August, and Uchijima (1976) investigated accumulated air temperature during the period when daily mean air temperature were above 10°C. However, these indices seem to be insufficient for explaining yield variation throughout the country. Thus, the author examines the variation of climatic productivity, the long-term variation and its geographical distribution in an attempt to provide more sufficient explanation of these variations.

2. Data and Methods of Study

Climatic data and method for establishing the regional division

Main regional division is based on the Y_p variational patterns (Sugihara and Hanyu, 1980), which indicate the difference in seasonal variation of climatic productivity.

The difference in temperature characteristics of Y_p must be further examined before sub-division. The Y_p variational patterns due to air temperature deviations of 1 or 2℃ from the normal during all growth stages are examined through data from 99 meteorological stations (refer to Appendix). The values of normal climatic elements such as; θ_R, S_R, θ_V, and θ_H at the normal SHP have been made available at those stations (Hanyu and Sugihara, 1981). Thus, the Y_p value of a tentative temperature change can be obtained through Equations (1) and (2).

Data and method to examine the validity of division

Yearly variation of Y_p from 1965 to 1979 was also investigated in order to examine the validity of agro-climatic division. Subject stations are the 36 main productive regions on a plain or basin scale. Y_p at the normal SHP are calculated using yearly data for the 36 meteorological stations in the regions.

Then, the mutual correlation between each of two time series of Y_p values are calculated. These correlation coefficients are regarded as an index of similarity, and are examined through the technique of hierarchical cluster analysis called the "Ward Method."

In order to clarify the characteristics of each agro-climatic division, yields, Y_p at the normal SHP, and climatic elements forming Y_p are examined for the 36 stations during 1965-1979 from two viewpoints: mean values and standard deviations (or the coefficients of variance).

In calculating the variance coefficients for yields, technical advance trends must be assumed. The stagnation model of t_8 (Sugihara and Hanyu, 1981) is assumed as the trend, and t_8 model is adopted as normal values.

Data and method for long-term variation

The following 6 meteorological stations serve as agro-climatic division representatives: (1) Asahikawa (Hokkaido), Type A1; (2) Morioka (Iwate Prefecture), Type A2; (3) Matsumoto (Nagano Prefecture), Type A3; (4) Niigata (Niigata Prefecture), Type B; (5) Ohita (Ohita Prefecture), Type C; and (6) Saga (Saga Prefecture), Type D. Y_{po} for each station is calculated using the data of its meteorological station, and yield representing each station is substituted for the mean yield of the administration unit shown in parenthesis.

The subject period is a period of 55 years from 1926 to 1980 and decade data during this period can be obtained from the climatic tables.

For calculating Y_{po}, decade mean air temperature data was utilized and the following source materials and data have been available: (a) for the periood of 1926 through 1952, "Decade meterological table"; (b) for the period since 1953, the decade data which was converted from the pentad value data issued in the "Annual Report of Meteorological Agency of Japan."

The mean yield of prefecture standard was obtained from the "Crop Annual Statistic Table for Paddy Rice" (Statistical Research Department of Agriculture and Forestry, 1955) and for period after 1955 from "Statistics of Crop" (the Ministry of Agriculture, Forestry and Fisheries). The unit used for yield data in the former, *Koku/Tan*, is converted into kg/10a as 1 *Koku*=150kg and 1 *Tan*=10a. The yield data are, as already mentioned, the mean value at prefectural level. The ratio of the yield for the middle year of each 11 year period to the running mean for the same 11 year period is termed the crop index (Y_i). In order to remove the trend of technical advance, Y_i is a subject of investigation.

The formula of Y_p and method of calculation have already been described but the reader will note that Y_p investigated in long-term change is the Y_{po} (the maximum value of Y_p) for each year.

Procedure of analysis is as follows:

1) Time-series of Y_{po} and yield (including their running means and variance coefficients over 11 years) are illustrated comparatively.

2) The running means and coefficients of variance of SHP in each stations are comparatively illustrated in the same figures.

Data and method for obtaining geographical distribution of Y_p variability

As a standard of the variational characteristics of θ_R and S_R, their standard deviation ($\Delta\theta_R$ and ΔS_R) for the 15 years after 1965 are examined at the 36 stations. However, M_G is not normally distributed in statistics, so the empirical return period of M_G must also be considered.

The empirical formula for calculating return period is:

$$\tau=2J/(2j\text{-}1) \qquad (4)$$

where J denotes statistical period of years, j the order from the largest or smallest and τ the return period for above or below the j-th value (Takeda, 1957, *et al.*).

Since return period $\tau=6.3$ corresponds to the probability of standard deviation, the M_G value of $j=3$ is regarded as a standard of M_G variation. Ratios of the 3rd values of M_G to the 8th (medium) are denoted by the symbol $M_{G,R}$. The $M_{G,R}$, when M_G is above the 3rd, is denoted by $M_{G,R}\downarrow$ because $M_{G,R}\downarrow$ is less than 100%. Conversely, when M_G is below the 3rd, it is denoted by $M_{G,R}\uparrow$ (more than 100%).

3. Agro-Climatic Division by the Climatic Productivity

The chief basis of division: Y_p variational pattern due to shift in heading periods

Since the climatic elements forming Y_p show seasonal variation (Figure 1), the Y_p variation due to differences in heading dates are shown in Figure 2. This Y_p variation can be classified into 4 types; A, B, C, and D (Hanyu and Sugihara, 1981).

Type A, represented by Yamagata, takes its maximum in the 1st to 2nd decade of August, and rapidly decreases toward the 3rd decade of September. Type B represented

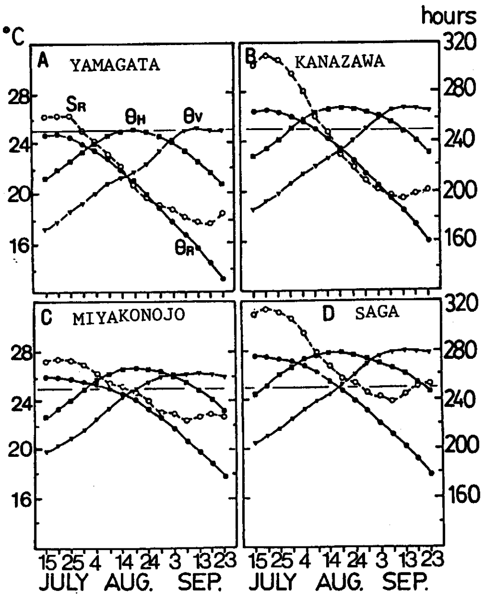

Fig. 1 Relation of θ_V, θ_H, θ_R and S_R to the heading dates.

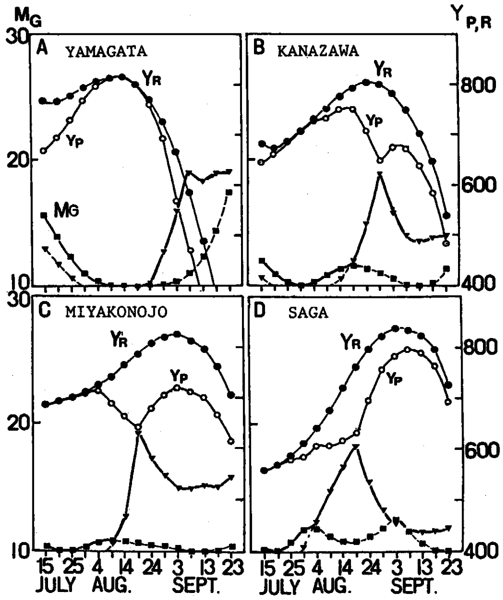

Fig. 2 Relation of Y_p, Y_R and M_G (M_V, M_H) to heading dates.

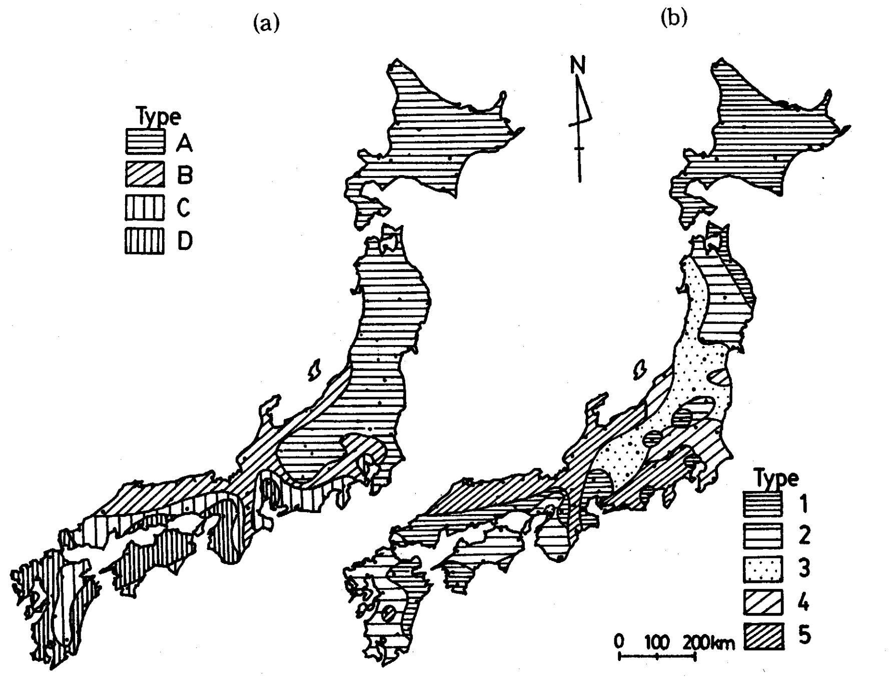

Fig. 3 Geographical distributions of Y_p variational patterns due to (a) shift of heading periods and (b) change of mean air temperatures.

by Kanazawa has a slump in the 3rd decade of August and a small secondary peak in the 1st decade of September. Type C, represented by Miyakonojo, has two peaks of the almost same height one at the end of July/the begining of August and the other in the 1st decade of September. Type D, represented by Saga, peaks in the 1st decade of September, and the 1st peak shown by type C disintegrates to an almost gentle slope from the 2nd decade of July to the 1st decade of August.

For types B, C and D, in Figure 2, M_G values of more than 15 is due to M_V in cases of θ_V being around 25℃.

Since the Y_p variation due to a shift in the heading period is dependent on regional climatic conditions, it is expected that the Y_p variation would show regional regularity. This geographical distribution of the variational Y_p pattern is illustrated in Figure 3 (a).

Type A, the cold, cool and Highland district type is distributed in Hokkaido, the Tohoku District, the eastern part of the Kanto District, and Nagano Prefecture.

Type C and type D, which are distributed in Tokai, Kinki, San'yo, Shikoku and Kyushu, are warm district types. These 2 types intermingle within the distribution area, but type C is mostly located in peninsulas or inland highlands and type D is located on the Nohbi Plain and most parts of the plains west of the Kinki District. Type C has been defined as the "double peak warm district type," and type D as "single peak warm district type."

Type B is regarded as the transitional type from type A to types C and D.

In Figure 3 (a), the cold district of type A, which includes Hokkaido, the Tohoku District, the northern Kanto District, the Boso Peninsula and the highland of central Japan, is regarded as one homogeneous region. However, it is not reasonable to regard Hokkaido and the Boso Peninsula as belonging to the same climatic division. Therefore, it is nesessary to prepare a secondary basis of division, which will relate to the yearly variation of Y_p.

The secondary basis of division : Y_p variational patterns due to tentative change of mean air temperatures

At the normal SHP, it is assumed that the mean air temperatures θ_R, θ_V, and θ_H change by deviations from the normal 1 or 2℃. In other words, the mean air temperature through the warm period drops or rises uniformly by the deviation increments. The Y_p calculated for each deviation ΔT is denoted by $Y_p(\Delta T)$. The ratio of $Y_p(\Delta T)$ to normal Y_{po} is similarly denoted by $Y_{pr}(\Delta T)$.

The geographical distributions of $Y_{pr}(-2)$, $Y_{pr}(-1)$, $Y_{pr}(+1)$ and $Y_{pr}(+2)$ are shown in Figure 4, where the areas with $Y_{pr}(\Delta T)$ exceeding 110% is coverd with black, and 105% with dots. By examining the distribution of $Y_{pr}(-2)$ in Figure 4(a), we see that in the Tokai District, the Hokuriku District and the San'in District there are some areas where the Y_p increases as the temperature decreases. These areas are restricted to the division of type B and type C. In contrast to $Y_{pr}(-2)$, the $Y_{pr}(+2)$ distribution shows that there are some areas over 110% in Hokkaido, the Shimokita Peninsula and the highland of central Japan over 1000m above sea level.

In Figure 5, the Y_{pr} variation under various mean temperature deviations is divided into five types. The Y_{pr} variation for Asahikawa, indicated in the graphs (a), is

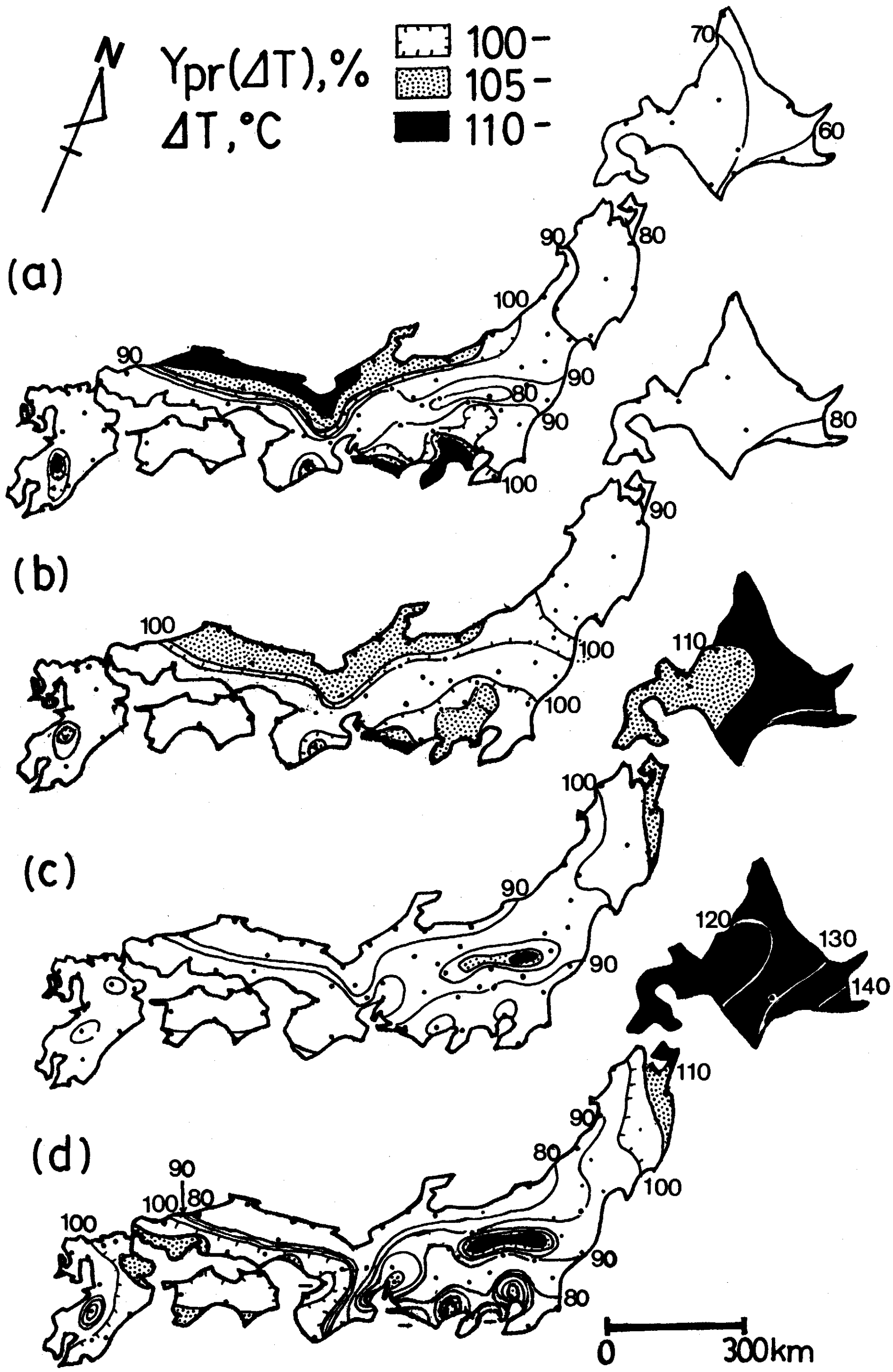

Fig. 4 Geographical distribution of (a) Y_{pr} (-2), (b) Y_{pr} (-1), (c) Y_{pr} $(+1)$, and (d) Y_{pr} $(+2)$.

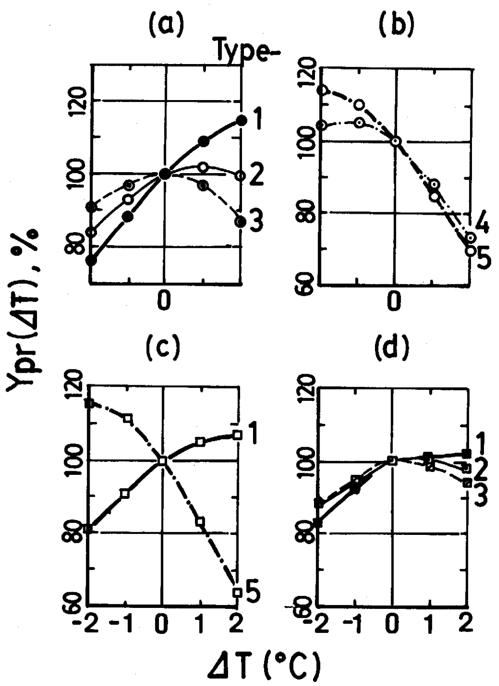

Fig. 5 Y_p variational patterns under various mean air temperatures in respective Y_p variational patterns due to shift of heading periods ;
(a) Type A, 1 : Asahikawa, 2 : Morioka, 3 : Matsumoto
(b) Type B, 4 : Maebashi, 5 : Hikone
(c) Type C, 1 : Ohita, 5 : Hamamatsu
(d) Type D, 1 : Miyazaki, 2 : Saga, 3 : Ohsaka

illustrative of type 1. The pattern of type 1 shows increases generally proportionate to increases in temperature. The Y_{pr} variational graph of Morioka illustrates type 2, which reaches its maximum value when $\Delta T = +1$℃. Type 3 is represented by the Y_p variation of Matsumoto, and its pattern takes a maximum value at the normal state, namely $\Delta T = 0$.

With respect to type B, two other patterns are illustrated in the graphs (b). The Y_{pr} variation of Maebashi is an example of type 4, which reaches its maximum when $\Delta T = -1$℃. Hikone is an example of type 5, where the Y_{pr} decreases with the increase in temperature.

The Y_{pr} variational patterns for types C and D, are illustrated in graphs (c) and (d).

Type 1 is regarded as the lowest temperature conditions. Type 2 is lower than type 3 which is considered the optimum temperature condition. Type 4 has higher conditions than type 3 and type 5 is the highest condition. The temperature conditions of each type are closely connected with the normal SHP, which occurs earliest for type A during the 1st decade of August and latest on for type D during the 2nd decade of September.

In Figure 3(b), the geographical distribution of the Y_p variational patterns under changing mean air temperature deviations are illustrated. Each type is distributed in series from Hokkaido to around 35°N, running along the Chugoku Mountains—Tokai District. But, to the south of the line the distribution suddenly returns to that of types 1 and 2. This discontinuity is caused by the difference in normal SHP. The normal SHP of types C and D is later than the 1st decade of September, and that of type B is earlier than the 3rd decade of August.

Agro-climatic division based on the Y_p index

The possible combinations of the two bases are summarized in Table 2, where the numbers of stations belonging to the combinations are written. The combinations A.5, B. 1, B.2, B.3, C.3, C.4, D.4, and D.5 are blanks in the columns of the table.

Table 2 Combinations of the two different patterns of the Y_p variation in 99 stations.

Types	A	B	C	D	Total
1	18	/	9	9	36
2	5	/	2	15	22
3	12	/	/	1	13
4	6	3	/	/	9
5	/	16	3	/	19
Total	41	19	14	25	99

The combination of A.4 is distributed from the Boso Peninsula to the northern Kanto District, and it is located under higher temperature conditions than the optimum. Consequentry A.4 is a warm district transference type, type B.

Type C has 2 divisions: type C (combinations C.1 and C.2) and type C5 (combination C. 5). The latter, however, may in the end be regarded as type B.

In type D, the combinations D.1, D.2, and D.3 are regarded as being in the same division because there is very little difference in $Y_{pr}(\Delta T)$ values.

In all, seven divisions A1, A2, A3, B, C5, C, and D were obtained. The geographical distribution of the seven divisions are illustrated in Figure 6.

The mean values and the variance values of the yield and Y_p are illustrated in Figure 7 and Figure 8. The values are grouped into climatic divisions where possible. In addition to the figures, in Figure 9 the mean air temperatures during the actual heading period are illustrated latitudinally.

The characteristics of agro-climatic divisions

Type A1 Located in cold districts such as Hokkaido and the Sanriku Coast and in highlands of more than 1000m in altitude, this type shows variance coefficients of Y_p or the crop index of more than 8% or 6%, respectively (Figure 7(c) or (d)).

Type A2 Extending along the basin of the Kitakami River up to the Tsugaru Peninsula and the Highlands above 400m in the Tohoku District, this division has the mean θ_R lower than 21.5°C (the optimum air temperature during ripening: *i.e.* θ_o, Figure 8(a)).

Type A3 Extending over regions from the coastland of the Japan Sea and the southern part of the Tohoku District to the highlands of central Japan, the Y_p and Y of this division are generally high with abundant sunshine (Figures 7(a), (b) and 8(c)).

Type B Located from Niigata to Shimane Prefectures along the Japan Sea, including the Kanto District and regions in the Kinki District such as Ohmi Basin, Ueno Basin and Owase. This climatic condition provides transition to warm districts. However, the mean

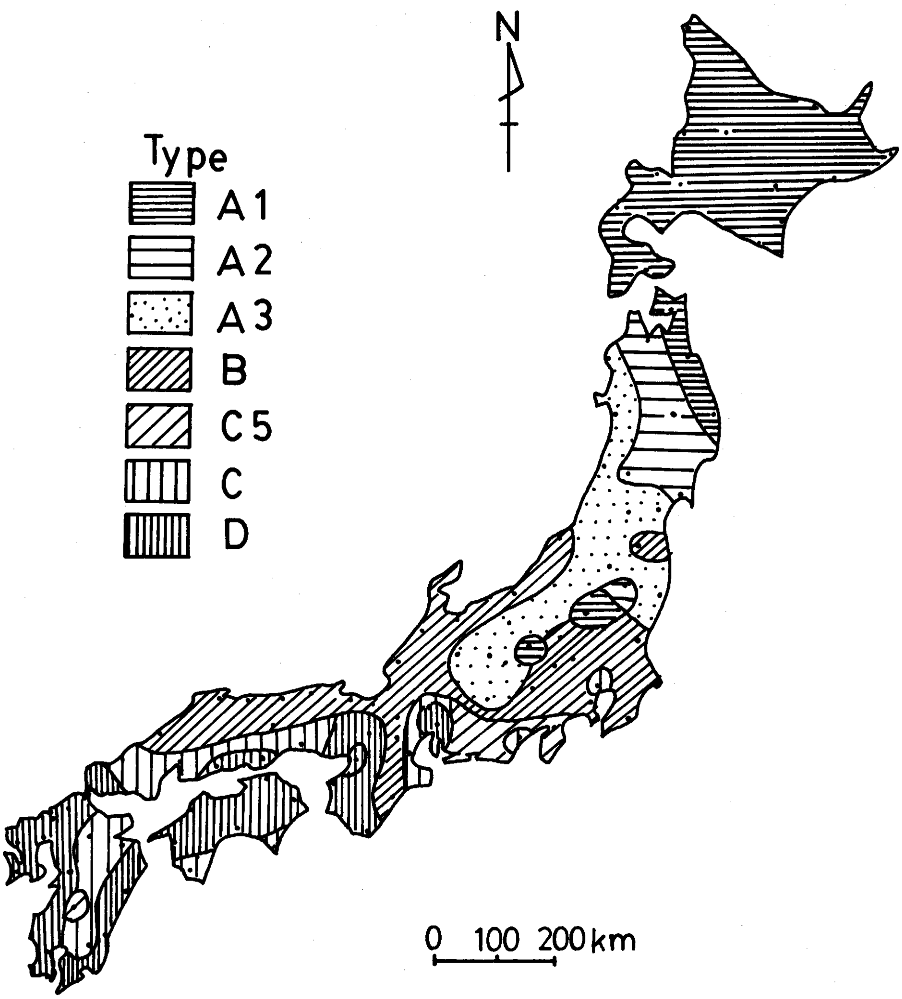

Fig. 6 Geographical distribution of agro-climatic divisions in terms of Y_p.

values of θ_R in this division (except regions where actual heading is later than SHP) are the highest (more than 23°C) (Figures 8(a) and 9).

Type C5 This set climatic conditions can be termed a semi-warm district located in narrow regions; namely a part of the Tokai District and Hitoyoshi Basin.

Type C This warm district is geographically located in Tokyo, Shizuoka, the western part of the Ise Bay coastland, most of the San'yo District, the southern tip of Shikoku and the highlands of Kyushu. This type C and the following type D geographically cross each other. But, Y_p in this type are generally lower than Y_p in type D because of higher values of M_G (Figures 7(a) and 8(e)).

Type D Located in the Nohbi Plain, and including almost all of the plains west of the Kinki District, this set of climatic conditions creates the warmest type of all.

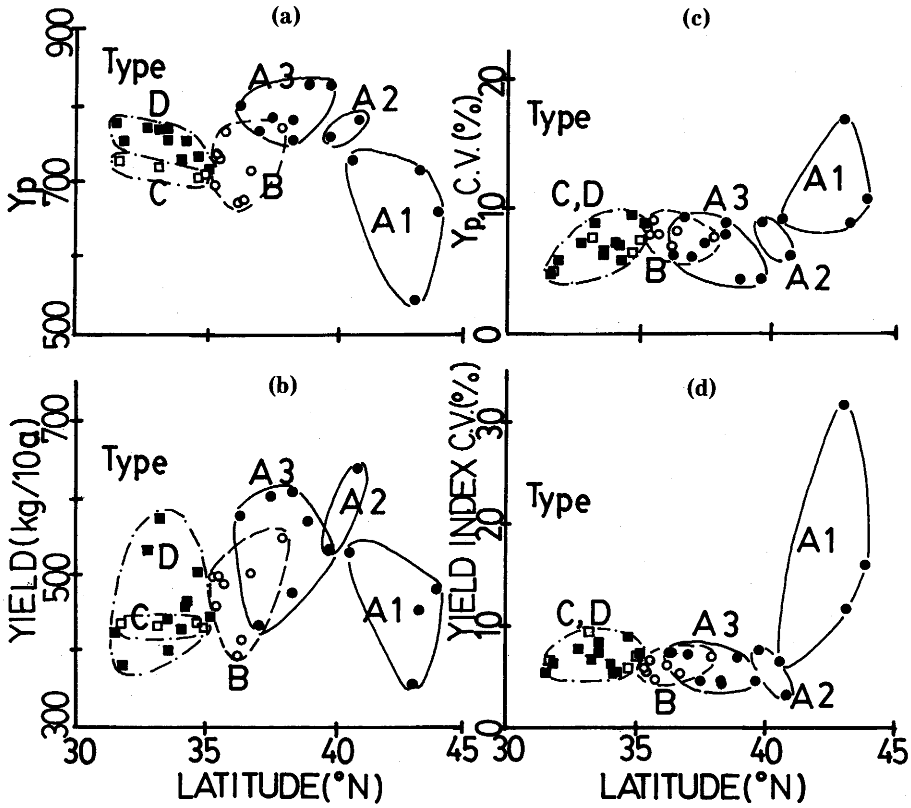

Fig. 7 Latitudinal distribution of (a) mean Y_p at normal SHP, (b) mean regional yield during 1965-1979, (c) coefficients of variance of Y_p at normal SHP, and (d) those of yield ratio, in 36 main paddy regions.

The regionality of Y_p based on sunshine conditions

Because there is a logarithmic relation between Y_p and S_R, Y_p variations due to various changes in S_R conditions resemble each other. But there is a quantitative difference in the sunshine conditions among 99 stations.

Denoting Y_{pr} at 60% normal S_R by Y_{pr}(60%) and that at 180% normal S_R by Y_{pr}(180%), the author illustrates their geographical distributions in Figure 10.

For Y_{pr}(60%), the areas with Y_{pr} over 85% are on the Akita Plain extending to the Shonai Plain along the Japan Sea coastland and also some other stations such as Matsumoto, Mishima and Hamamatsu. The areas with Y_{pr} over 84% have sufficient sunshine hours.

In contrast, the areas under 83% include Hokkaido (except for the Ishikari River basin and a part of the Oshima Peninsula), the central highlands, Tokyo, Tottori and insidal basins of Kyushu. Sunshine conditions in these areas play a particularly important part in maintaining climatic productivity.

The above mentioned regionality is also seen for Y_{pr}(180%). Areas with less than 117% are abundant in sunshine. In contrast, areas of more than 120% are in want of sunshine.

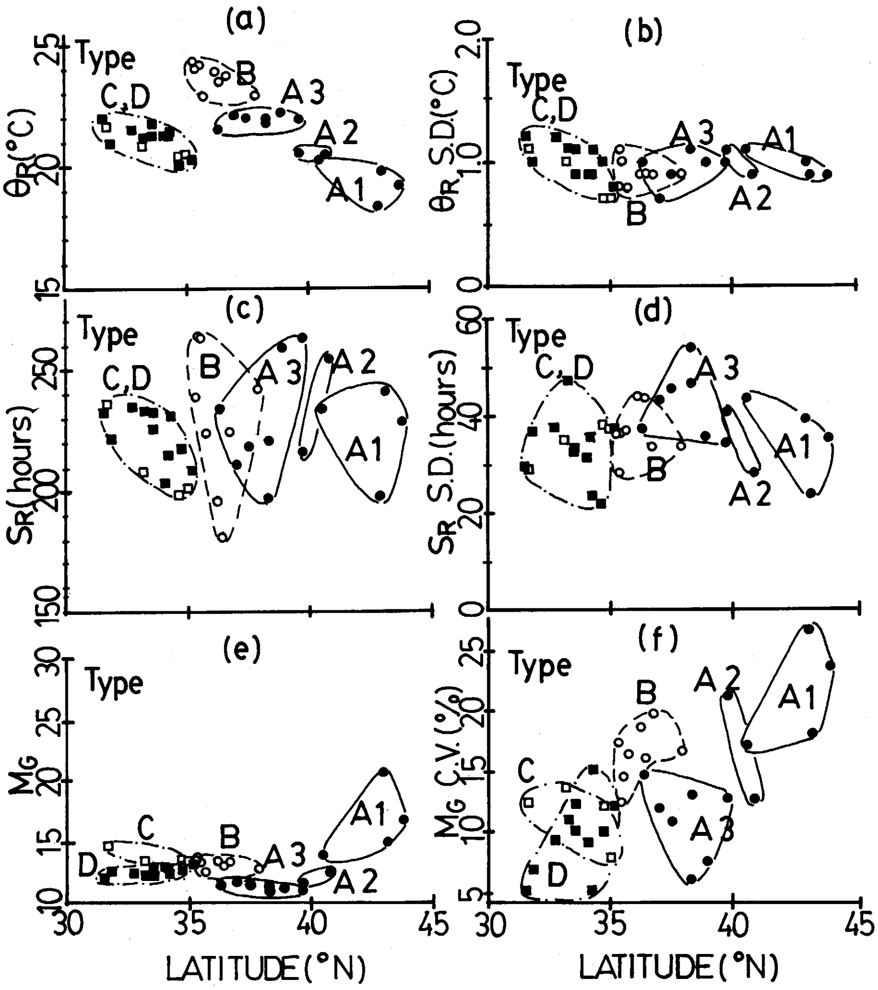

Fig. 8 Latitudinal distribution of (a) mean θ_R, (b) standard deviation of θ_R, (c) mean S_R, (d) standard deviation of S_R, (e) mean M_G, and (f) coefficients of variance of M_G.

This contrast is most clearly seen for type B.

The difference in sunshine conditions may be adopted as a third basis of divisions. However, such a 3rd division becomes too complex with the difference of the values in Y_{pr}(60%) or Y_{pr}(180%) being a few percent, so the author has regarded the regionality of sunshine conditions as the difference in climatic productivity for the same agro-climatic divisions.

Regionality based on yearly variation of climatic productivity

Using normal climatic data, the author has established the agro-climatic divisions by means of Y_p. Y_p temperature characteristics for temperature deviations are secondary, but it does not necessarily follow that the divisions are equivalent to the regions created

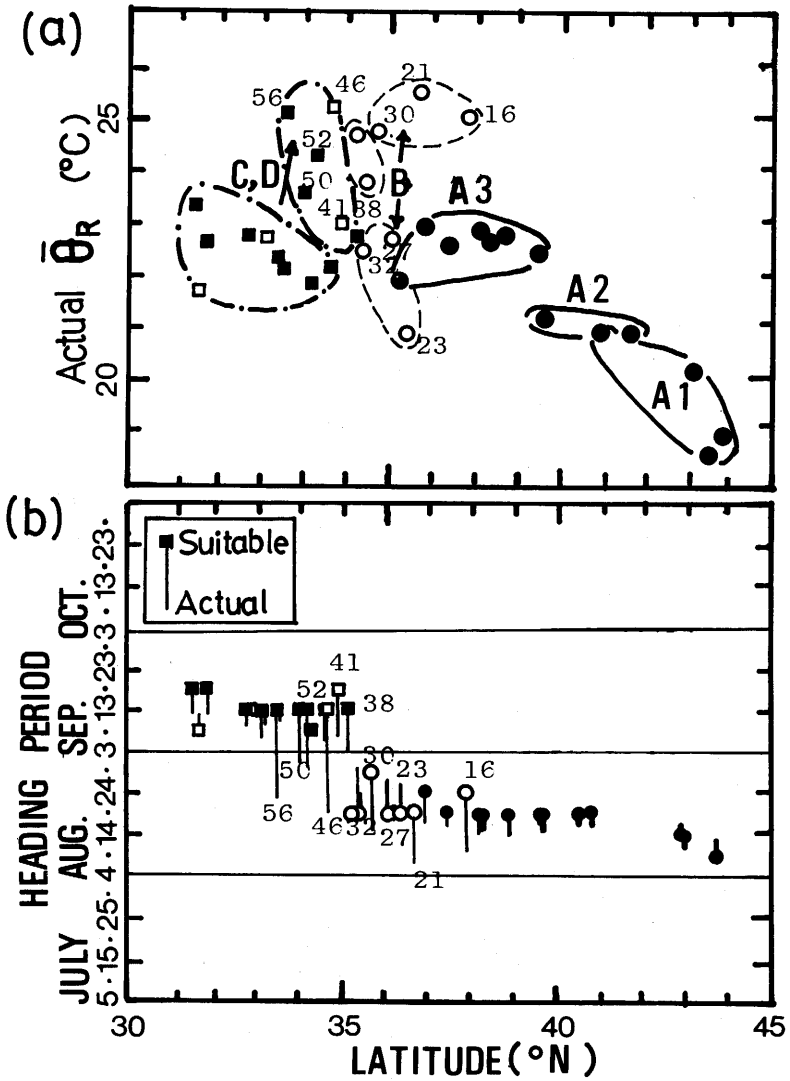

Fig. 9 Latitudinal distribution of (a) mean θ_R at actual heading period, and (b) normal SHP and mean actual heading periods in 36 main paddy regions.

by yearly Y_p variation.

The 36 main paddy regions are classified into 7 agro-climatic divisions, which are symbolized in Figure 11(a). There is no station for type C5 in the 36 main paddy regions.

The result of classifying yearly variation is shown comparatively by cluster analysis in Figure 11(b), where the clustering ends at the 27th stage with respect to 36 regiond so that 9 clusters (C1-1, C1-4, C1-11, C1-12, C1-15, C1-18, C1-25 and C1-32) are obtained.

Figure 11 compares the two kinds of regionality mentioned above, and the mutual relation between them can be pointed out as follows:

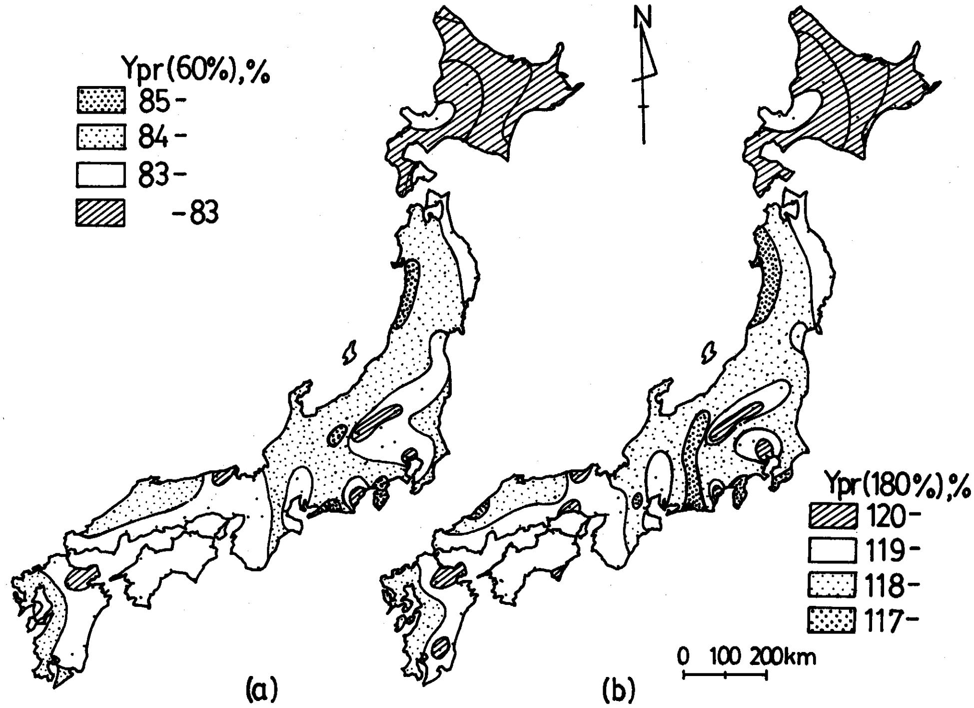

Fig. 10 Geographical distribution of Y_{pr} when the ratio of S_R to the normal is (a) 60%, and (b) 180%.

1) Type A1 to C1-1, 2) Type A2 to C1-4, 3) Type A3 to C1-6 and C1-11,
4) Type B to C1-12 and C1-15, 5) Type C to C1-18, and
6) Type D to C1-25 and C1-32.

Some questions are raised by the relation shown above. For instance, C1-1 is restricted to Hokkaido, but type A1 includes the Sanriku Coast. Type A2 seems to be more similar to type A3 than type A1 with respect to the Y_p yearly variation. Therefore it seems that type A3 should be divided into two portions, C1-6 and C1-11. But C1-11 contains two stations of type B, Choshi and Hikone. Type B should also be divided into two, the Kanto District (C1-12) and the Japan Sea coastlands (C1-15).

When we compare the agro-climatic divisions with clusters due to yearly variation by means of the comparable symbols used in Figure 11, 75% of all pairs symbols are the same. By recognition of internal differences in types A3 and B divisions, the agro-climatic divisions established in this chapter correspond to the regionality of the yearly variation in Y_p.

Conclusion

The agro-climatic division based on two kinds of variation in Y_p patterns: heading period shifts and normal mean air temperatures changes is established. Seven divisions, types A1, A2, A3, B, C5, C and D (Figure 6), were established.

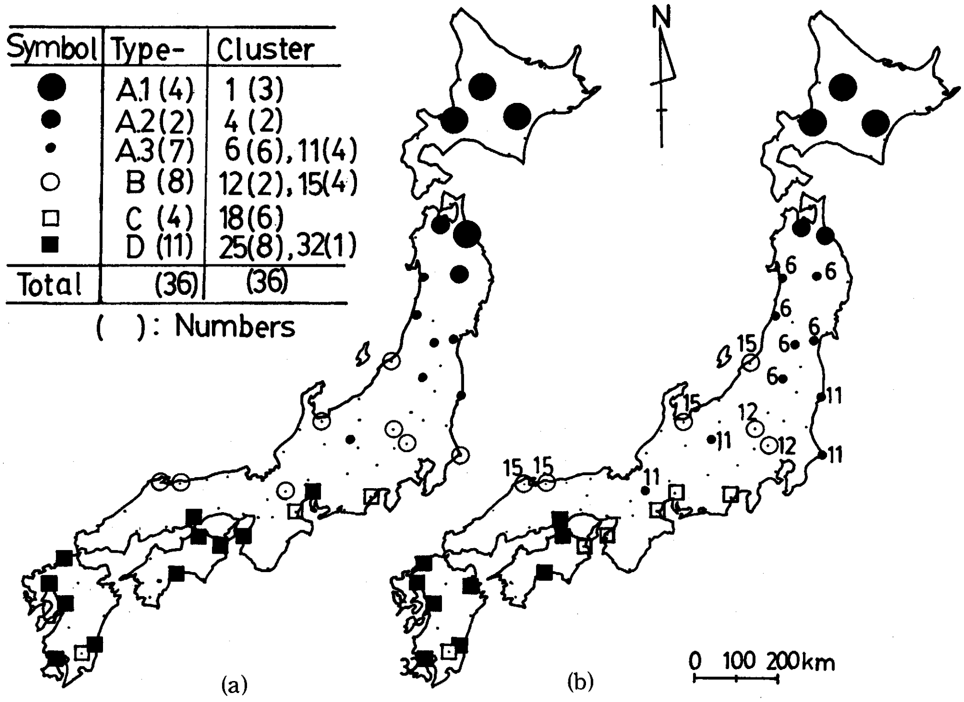

Fig. 11 Geographical distribution of (a) each agro-climatic division and (b) each cluster due to the time-series in 36 main paddy regions.

The characteristics of each division are summarized as follows:

Type A1 The coldest and the highest highland regions. The variance coefficients of the yield ratio and Y_p are the highest here (6% and 8%, respectively), so that there exists a risk of cool summer damages. The cause of limiting factors come from the lowest θ_R (less than 20°C) and the greatest variation in M_G.

Type A2 The cold, highland region, where θ_R is lower than $\theta_o = 21.5$°C. The maximum Y_p variation due to mean air temperature changes appears at deviation from the normal of +1°C.

Type A3 Cool region, although temperature conditions are optimum for paddy rice. Because the largest climatic productivity index appears in this division, provided there is abundant sunshine, the greater part of the high-yield paddy rice regions in Japan exist here.

Type B Transitional to warm district. θ_R, however, is the highest because of seasonal delay in the normal SHP in warm districts (types C and D). Most early delivery rice regions are here but regions whose mean actual heading period is later than the normal suitable one also exist here.

Type C5 Sub-warm district. The seasonal Y_p variation shows binaural maxima, and the normal SHP is incident to the former peak. Consequently, this type may eventually be included in type B.

Type C Warm district. The seasonal Y_p variation shows binaural maxima like type

C5, but the normal SHP is incident to the latter peak. The Y_p value of this type is less than that for type D because of greater M_G.

Type D The warmest district. Although the maximum Y_p in this division is usually higher than those of types B and C, there are several lower yield regions where the actual heading period seems to be too early to show the climatic productivity.

Regionality based on sunshine conditions was considered, but it was not adopted as a third basis for division because of its small differences. However the difference in sunshine conditions were not so negligible for type B in Y_p yearly variation.

Agro-climatic divisions were compared with the regions based on Y_p yearly variation by cluster analysis (Figure 11). As a result of comparing each pair of marks symbolizing each division or cluster, assuming the internal regionality of type A3 and type B, they agreed in 75% of all stations.

The agro-climatic divisions considered in this chapter could reveal some new ideas about regionality of yearly variation and possibly enable us to grasp climatic productivity of paddy rice for all Japan using several sample stations.

4. Long-term Change of Climatic Productivity

Long-term change of Y_{po}

The following items are illustrated in Figure 12; a) Y_{po} time-series and their running means and variance coefficients, b) Yield time-series, their running means and variance coefficients for each of the subject stations.

The various time-series for Asahikawa (Hokkaido) are shown in Figure 12(a), with the long term Y_{po} change of Asahikawa shown in the upper portion with running means drawn in heavy line, which takes its minimum in the first half of the 1930s and 1960s. In the second half of the 1930s, paddy fields in the marginal regions of Hokkaido were abandoned on a large scale (Okamoto, 1965). Particularly, the cool summer damage of 1931 resulted in the poorest climatic productivity over the subject period. The minimum of Y_{po} in the 1960s seems to be peculiar to Hokkaido, and the Y_{po} of Morioka shows no decrease. The maximum Y_{po} in Asahikawa appears in the second half of the 1940s when rice production rapidly increased. The same maximum can be seen in Morioka in Figure 12(b), and it was fortunate to maintain the highest level of Y_{po} for northern areas of Japan during the post-war food-shortage.

On looking at the variance coefficient of Y_{po} (20% in Asahikawa or 13% in Morioka), it is observed that it reaches its maximum in the 1930s for both stations. Conversely, it reaches its minimum in Asahikawa around 1970, and in Morioka in the second half of the 1960s. This corresponds to the period that decrease of paddy field and production adjustment had been commenced on the assumption of rice over production. This period represents the most stable agro-climatic conditions in the last 50 years. Y_{po} for Morioka in 1976 and 1980 show the lowest values during the subject period.

Y_{po} long-range change for Matsumoto in Figure 12(c) and that for Niigata in Figure 12(d), shows variations of only 5% and 7%, respectively. However, Y_{po} drop for Matsumoto in 1980 is greatest ever.

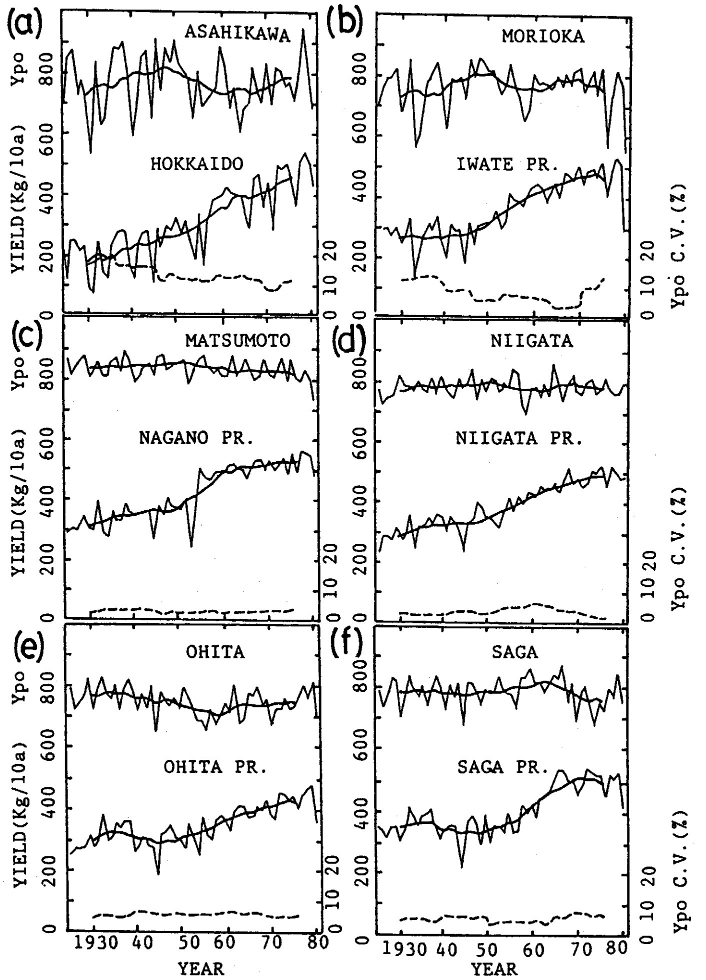

Fig. 12 Time-series of maximum Y_p (Y_{po}), prefectural yields, their 11-year running means, and coefficients of variance of Y_{po} at each station which represents each agro-climatic division.

In examining long-range Y_{po} variation in the warm districts of Ohita and Saga, it is seen that Ohita's minimum Y_{po} occurred during the second half of the 1950s, and in Saga Y_{po} reached its maximum in the middle the 1960s. At that time, Saga Prefecture became most productive and the cultivating system of Saga was dubbed the "new Saga stage." The peaking of Y_{po} played an important part in the high yields which occurred at that time. The variance coefficients Y_{po} for the two stations are 7% and 8%, respectively.

Long-range change in SHP is summarized in Figure 13. Ohita (type C) clearly shows a change. From the 1940s to the first half of the 1950s Ohita shows type C5 or type B of Y_p variation according to heading periods. The Y_p variational pattern of type C seems to be susceptible to change due to yearly fluctuations from the normal of the mean air temperature (θ_V) or total duration of sunshine (S_R), so that the SHP of Ohita is also most

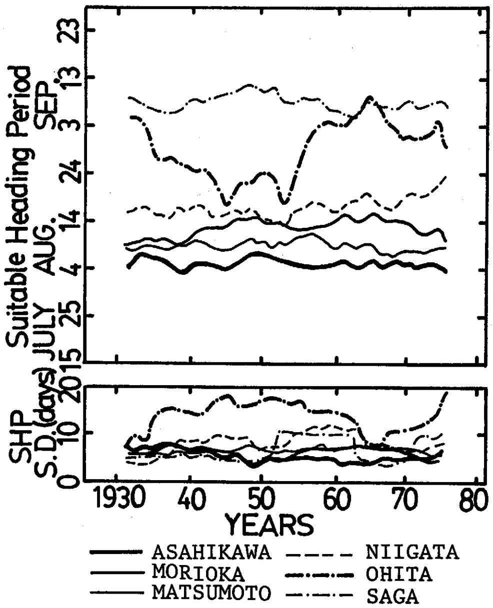

Fig. 13 Long-term change in SHP and SHP standard deviation at 6 stations.

susceptible to change.

Due to the cold climate of the 1930s, the SHP in Morioka seems earlier during that decade than in later periods. However, the SHP of Asahikawa did not occur earlier because cold temperature (θ_V) restricts the advance of SHP.

Conversely, the stability of SHP is indicated by the maximum standard deviations of SHP about 8 days in Asahikawa, Morioka and Matsumoto, 11 days in Saga, 12 days in Niigata and 19 days in Ohita. Thus, the stability of SHP in each division takes the following order: (1) types A1, A2 and A3; (2) type D; (3) type B; and (4) type C.

Correlation between Y_{po} and relative yields

The fluctuations in Y_{po} and the mean prefectural yield at representative stations are compared. For instance, for Ohita (Figure 12(e)), the relation between Y_{po} and Y seems to depend on a difference in the periods before and after about 1946 when the yield level reveals remarkable improvement. The ratio of yield to the running mean value for 11 years is defined as the crop index (Y_i). The correlation between Y_{po} and Y_i is denoted for the following three different periods;

1) full period (1926 through 1980),

2) before 1946, 3) after 1947 (Table 3).

The second period shows the most proper correlation in general.

In this regard, while there seems to be a steady effect of technical factors keeping the yield level up after 1947, the paddy rice production before 1946 seems to be strongly affected by natural surroundings (climatic productivity, *etc.*).

Table 3 Correlation coefficients over the following different periods between Y_{po} and Y_i in main paddy regions representing the agro-climatic divisions.

Regions \ Periods	1926–1980	1926–1946	1947–1980
Asahikawa	0.818	0.879	0.733
Morioka	0.762	0.876	0.665
Matsumoto	0.398	0.593	0.344
Niigata	−0.089	−0.049	−0.144
Hikone	0.118	0.437	−0.082
Ohita	0.375	0.749	0.151
Okayama	0.289	0.548	0.174
Kohchi	0.193	0.346	0.054
Saga	0.456	0.580	0.347

Conclusion

The long-range change of the climatic productivity index was examined by viewing its running means as typical stations representing agro-climatic divisions. Within the subject period (1926-1980) the long-range changes in Asahikawa, Morioka, and Saga clearly indicate maximum or minimum values substantially affecting the production of paddy rice.

During the 1930s, minimum Y_{po} in Asahikawa resulted in paddy fields within the marginal regions of Hokkaido being abandoned in a large scale.

Maximum Y_{po} are seen at two different periods in Morioka; the former (the 2nd half of the 1940s) contributed to the post-war yield increase and the latter (the 2nd half of the 1960s) introduced the policy of decreasing paddy fields because of "surplus rice." However, during the latter period, the climatic productivity is the most stable (*i.e.* variance coefficients are the least) of all subject periods. In the 1970s, the climatic productivity of Morioka is comparable to the minimum of the 1930s.

Saga, a warm district type, also reaches its maximum Y_{po} in the middle of the 1960s, when Saga Prefecture became the highest yielding prefecture of Japan, and its cultivation technique was called the "new Saga stage."

The maximum coefficient variance of Y_{po} generally appears during the minimum period of Y_{po}, and the maximum percentage of each station is as follows:

Asahikawa 20%;
Morioka 13%;
Matsumoto 5%;
Niigata 7%;
Ohita 7%;
Saga .... 8%.

Conversely, the minimum coefficient appears during the maximum period of Y_{po}, when cultivation techniques are usually advancing.

In examing long-range change in SHP, a clear change was only obtained for type C, Ohita. The pattern of type C is most susceptible to yearly fluctuation of climatic elements forming Y_p. In contrast, the stability of SHP is indicated by the minimum standard deviations of SHP. The order is as follows:

1) Asahikawa (Type A1), Morioka (Type A2), and Matsumoto (Type A3) ··about 8 days;
2) Saga (Type D) ·························11 days;
3) Niigata (Type B) ·······················12 days;
4) Ohita (Type C) ·························19 days.

Finally, the correlation between Y_{po} and relative yields (Y_i) was summarized in Table 3. The best correlations were found in the period before 1946. Technical factors exert a steady relative effect keeping the yield level up after 1947 but paddy rice production before 1946 was affected more by natural surroundings (climatic productivity, *etc.*). Climatic productivity seems to restrict reletive yields in the following order;

1) Asahikawa (Type A1); 2) Morioka (Type A2);
3) Saga (Type D) and Matsumoto (Type A3);
4) Ohita (Type C); 5) Niigata (Type B).

The order also seems to show the degree of correspondence of actual cultivating varieties to Y_p.

5. Geographical Distribution of Variability of Climatic Productivity

Introduction

If we know in detail the geographical distribution of variational characteristics of Y_p, this will be basic material data which shows the fluctuations from the normal potential productivity viewpoint of paddy rice. In addition, if we know which element forming Y_p essentially restricts the productivity in each agro-climatic division, we may determine the technical purpose for removal of impeding factors of climatic productivity.

In this chapter, the variational characteristics of climatic elements; such as θ_R, S_R, and M_G, according to the agro-climatic divisions represented in Chapter 3 are first examined to obtain the geographical distribution of composed fluctuation of Y_p by composing the variance of them on the basis of the Y_p equation. Next, the correlation between climatic elements is examined.

On the other hand, it seems that the values of θ_R and S_R during the ripening period are closely related and this relation affects normal SHP, so that the correlation between θ_R and S_R should be examined for each agro-climatic division. The normal SHP in the divisions of types A1, A2, A3, B, and C5 are in mid-summer, and those of types C and D seem to be during the Shurin season.

However, as a correlation between an element M_G before heading and elements θ_R or S_R after heading cannot be found, they are treated on the assumption of their independence.

Finally, the Y_p values for certain return periods for respective agro-climatic divisions are examined empirically (according to Equation 4) and theoretically. The theoretical way of their estimation is based on the assumption of the normality of Y_p distribution.

Climatic data used for calculating Y_p are θ_R, S_R, θ_V, and θ_H based on the normal SHP.

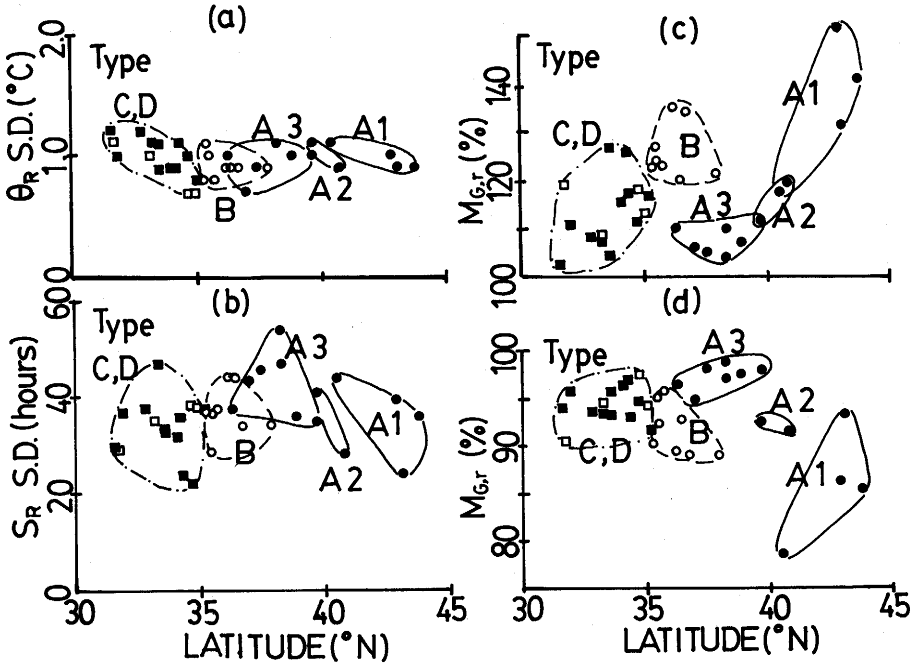

Fig. 14 Latitudinal distribution of (a) θ_R standard deviation, (b) S_R standard deviation, (c) $M_{G,r}\uparrow$, and (d) $M_{G,r}\downarrow$, in each agro-climatic division.

These are calculated from pentad normals (Japan Climatic Table Part 4, Japan Meteorological Agency, 1971). Data defining one unit variational range $\Delta\theta_R$, ΔS_R, or $M_{G,r}$ were already obtained in the statistical range of 15 years, 1965 through 1980. Their latitudinal distributions are illustrated in Figure 14.

Natural seasons progression in warm period is examined using the minimum values of 5-term running means of pentad means averaged over the 15 years for the 36 stations. Annual pentad data of total duration of sunshine and mean air temperature (Annual Report of Japan Meteorological Agency) are utilized during the statistical range.

Two kinds of heading periods, the normal SHP and the mean of actual dates, are contrasted with the natural season. These were already obtained in Chapter 3 and illustrated in Figure 9(b) as latitudinal distribution.

Finally, the time-series of the Y_p at the normal SHP in Asahikawa, Morioka, Matsumoto, Niigata, Ohita and Saga over the period of 55 years are used to estimate the return periods for Y_p.

Geographical distribution of Y_{po} considering independent elemental variation

Concerning elemental variation, one unit variational range (OUVR, which is probability of 1/6) has already been defined as $\Delta\theta_R$, ΔS_R, or $M_{G,r}$. In this chapter, the maximum OUVR within each agro-climatic division is regarded as the potential OUVR of the division, which is represented in Table 4. The Y_p values calculated for each

Table 4 The maximum one unit variational range of various climatic elements in resepective agro-climatic divisions.

Type	$\Delta\theta_R$ °C	ΔS_R hours	$M_{G,r}\uparrow$ %	$M_{G,r}\downarrow$ %
A 1	1.11	43.6	151.3	78.5
A 2	1.04	40.8	119.1	91.5
A 3	1.10	53.8	111.7	94.8
B	1.10	44.1	134.9	88.9
C 5	1.10	44.1	134.9	88.9
C	1.07	32.5	126.4	90.4
D	1.24	36.5	118.9	92.9

element varied from the normal by each potential OUVR is denoted by $Y_p(\Delta\theta_R)$, $Y_p(\Delta S_R)$, or $Y_p(M_{G,r})$ and its ratio to normal Y_{po} by $Y_{pr}(\Delta\theta_R)$, $Y_{pr}(\Delta S_R)$, or $Y_{pr}(M_{G,r})$.

Y_p variations based on decreasing θ_R and S_R, and increasing M_G are obtained in Figure 15, where the order is as follows: (a) $Y_{pr}(-\Delta\theta_R)$; (b) $Y_{pr}(-\Delta S_R)$; and (c) $Y_{pr}(M_{G,r}\uparrow)$.

$Y_{pr}(-\Delta\theta_R)$ of type B division in Figure 15(a) increases to be more than 100%, but the other ratios for type B decrease to be less than 100%. The result mentioned above, however, is reasonably obtained from the Y_p equation (Equations 1 and 2 and the higher air temperature conditions of type B (refer to Figures 5(b) and 8(a)).

Figure 15 shows that OUVR of M_G most profoundly influences the decrease of Y_p in general. Particularly, $Y_{pr}(M_{G,r}\uparrow)$ is less than 90%, throughout the type A1 division. This, however, comes from over estimation of potential OUVR in type A1 which is actually the $M_{G,r}$ for Obihiro. It is inferred from the latitudinal dependence of $M_{G,r}$ that areas with less than 90% are restricted to regions excluding the core paddy region (bounded with dotted line) of Hokkaido (Figure 15 (c)).

In type A2 and type A3, however, OUVR of S_R is most influential because of the smallest value of $M_{G,r}\uparrow$ relative to ΔS_R. On looking at the divisions of types C and D (warm districts), the variations in M_G and S_R are equally effective in the Y_p decrease.

Y_{pr} distribution for converse change in climatic elements are illustrated next as (a) $Y_{pr}(+\Delta\theta_R)$, (b) $Y_{pr}(+\Delta S_R)$, and (c) $Y_{pr}(M_{G,r}\downarrow)$ in Figure 16. This shows the factor most effective in increasing climatic productivity to be M_G in type A1, but S_R in the other divisions.

Correlation between θ_R and S_R

A positive correlation is expected to exist between mean air temperature and total duration of sunshine during the ripening period. When correlation between θ_R and S_R is examined during the statistical period (1965-1979) for the subject 36 stations in main paddy regions, the correlation coefficient is found to be unexpectedly low as $r=0.172$ (significant at 1% level;**).

On the contrary, when the author classified the correlation between θ_R and S_R into respective agro-climatic divisions, as shown in Figure 17, the correlation coefficients were found to be around 0.4(**) in types A1, A2, A3, and B. In contrast, slightly negative

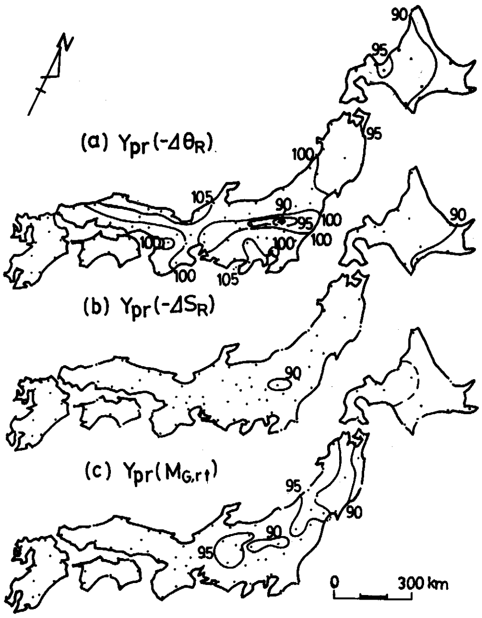

Fig. 15 Geographical distribution of Y_{pr} (in percentage) in case of one unit variational range (OUVR) of the following elements; (a) $-\Delta\theta_R$, (b) $-\Delta S_R$, and (c) $M_{G,r}\uparrow$.

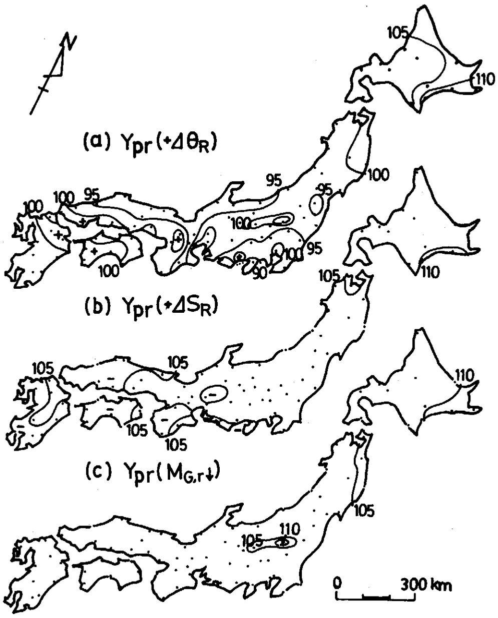

Fig. 16 Same as Fig. 15 but for (a) $+\Delta\theta_R$, (b) $+\Delta S_R$, and (c) $M_{G,r}\downarrow$.

correlation cofficients (significant at 5% level;*) are seen in types C and D.

The tendency mentioned above is also found for the individual stations within the agro-climatic division. For instance, Sendai, in the type A3 division, shows a correlation coefficient as high as r=0.743(**), whereas Miyazaki in the type D division shows a negative value of r=−0.624(**).

The regional difference in the correlation between them seems to come from the seasonal difference of the normal SHP which defines the climatic elements. Since the normal SHP starts in mid-summer, the correlation between them indicates positive coefficients. On the other hand, for types C and D in years when the Shurin season is earlier than normal, it seems that S_R increases but θ_R decreases under the late autumn chilled air masses from the continent. This is because more of the number of days during the ripening period belongs to the late autumn season.

The transition of pentad mean air temperature and total duration of sunshine in Miyazaki is illustrated in Figure 18 for years 1965 and 1970. The S_R of 1965 is more than the mean value and that of 1970 is less. For duration of sunshine, 3-term running means are shown by the solid lines. The minimum of the running mean is found during the 3rd decade of June in both years, and it seems to agree with the height of Baiu. The 2nd minimum during the 2nd decade of September in 1965 seems to represent the height of Shurin. Then, the late autumn season seems to start during the 1st decade of October. In

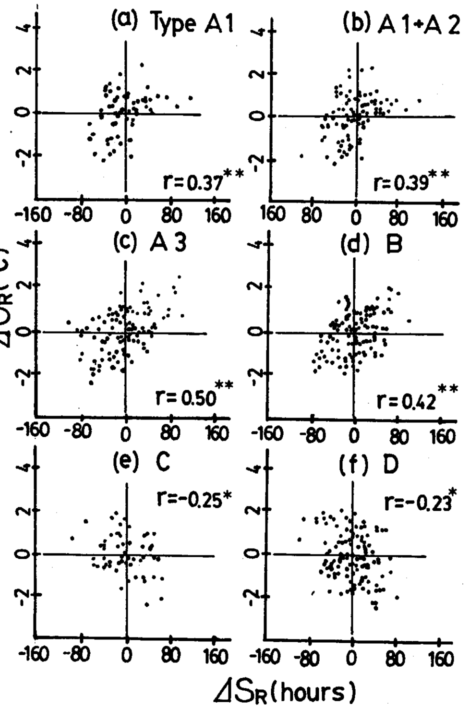

Fig. 17 Correlation between deviation of θ_R and S_R for each agro-climatic division. (a) Type Al; (b) Types Al and A2; (c) Type A3; (d) Type B; (e) Type C; and (f) Type D. (*significant at 5% level; **at 1% level)

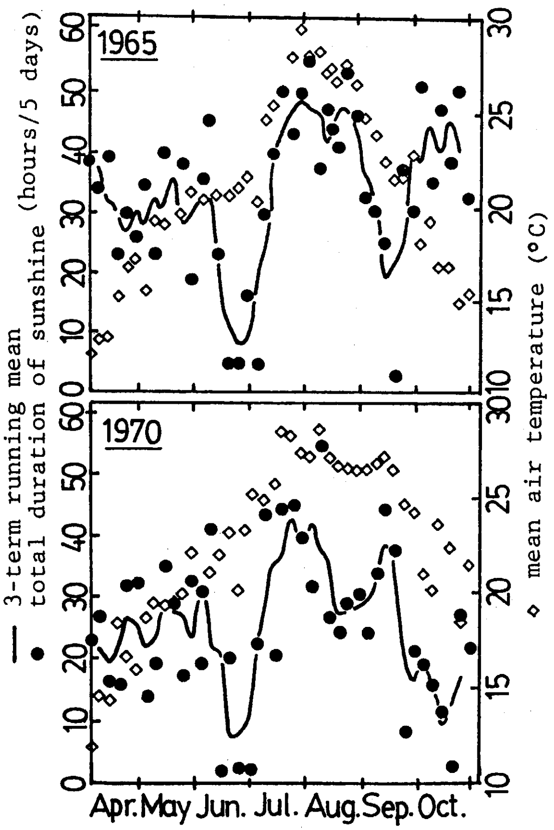

Fig. 18 Comparison of seasonal variation of pentad total duration of sunshine and mean air temperatures in Miyazaki for the abundant S_R year 1965 and poor S_R year 1970.

1970, the 2nd minimum of the running mean is found during the 2nd decade of October, the Shurin season is dragging on and the change to late autumn season is delayed.

Next, by comparing the seasonal change of pentad mean air temperature for both years, it is found that mean air temperatures decrease rapidly according to seasonal change to late autumn in 1965 but decrease slowly according to the delayed chage to late autumn in 1970.

This method, defining the height of Shurin and Baiu in Miyazaki in individual years, is used for the purpose of defining a mean best season for main paddy regions all over the country. Data utilized here are pentad data for 15 years from 1965, and the result obtained from them is illustrated in Figure 19.

The height of the Baiu season starts in Kyushu during the 3rd decade of June, and reaches Sapporo during the 1st decade of July. The symbols at the center of Figure 19 show normal SHP; and the ends of segments show the mean actual heading periods on a prefectural level. The upper symbols show the height of the Shurin season, namely the second minimum of running means for averaged duration of sunshine over the 15 years. The height of the Shurin season is seen in Hokkaido during the 1st decade of September, and during the 1st decade of October in Kyushu. The length of the Shurin season cannot be estimated with this figure, but Maejima (1967) suggested 38 days to 43 days throughout the country.

The mutual relation between the date of the normal SHP and the height of the Shurin season is summarized as follows: 1) the former is earlier than the latter by 5 to 45 days; 2) in types C and D divisions the differences between the two are smaller in general (5 to 25 days); 3) in the plains of Nohbi(38), Ise(41), Wakayama(50), Tokushima(52), and Kochi(56), and Enshu-Nada Coast(38), the mean actual heading periods are earlier than the normal SHP by 10 to 25 days and the difference between the two are at least 5 to 15 days.

This last point intends to infer that the mean actual heading period is advanced to avoid damage from bad weather including typhoons which often occur at the height of Shurin season.

Geographical distribution of Y_{pr} in considering the correlation between θ_R and S_R

By considering the correlation between θ_R and S_R in each agro-climatic division, one variable either θ_R or S_R can be reduced. Thus, the remaining two variables, namely M_G and θ_R (or S_R as the case may be) may be assumed to be independent of each other.

However, the relational equation between θ_R and S_R differs according to which of them

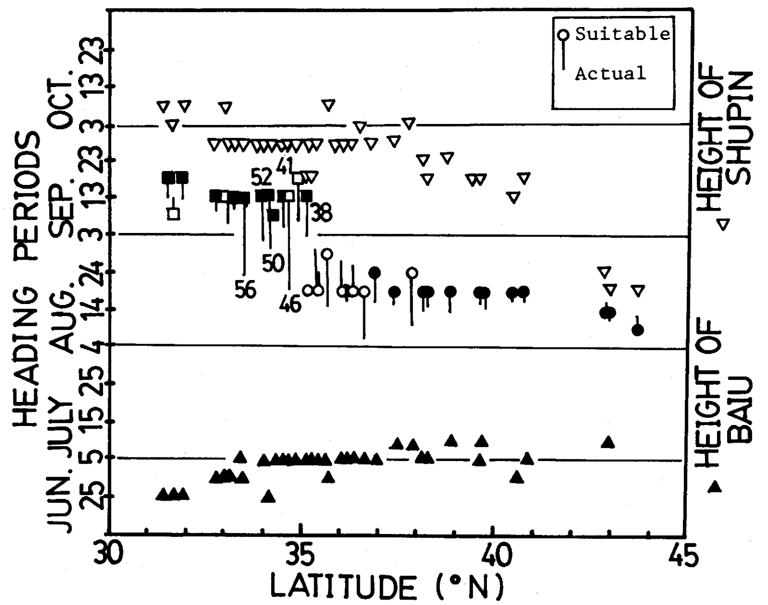

Fig. 19 Latitudinal distribution of height of Baiu and Shurin, and the normal SHP and the mean actual heading period for the main paddy regions of Japan.

is regarded as independent. When OUVR of θ_R from the normal is assumed, the other variable is estimated by multiplying the coefficient represented in Table 5, *i.e.* as AT1 $\times \Delta\theta_R$. In addition, the ratio of Y_p change to the normal Y_{po} in the case of M_G at the normal is denoted by $Y_{pr}(\Delta\theta_R, S_R)$. Similarly assumed S_R variation is denoted by $Y_{pr}(\Delta S_R, \theta_R)$.

The geographical distribution of $Y_{pr}(\Delta\theta_R, S_R)$ is illustrated in Figure 20. When θ_R is decreased by OUVR, the variational ratio is denoted by $Y_{pr}(-\Delta\theta_R, S_R)$, which is illustrated on the left hand of the figure. Similarly, $Y_{pr}(+\Delta\theta_R, S_R)$ is illustrated on the right hand. In spite of only OUVR or θ_R, because of correlation with S_R, the areas of Y_{pr} less than 90% expands over the eastern part of Hokkaido. This decreasing rate is same as $Y_{pr}(M_{G,r}\uparrow)$ shown in Figure 15(c). Due to the effect of the decrease of θ_R being superior to S_R type B (b) is slightly above 100%. As to the types C and D, $Y_{pr}(-\Delta\theta_R, S_R)$ shows higher values than $Y_{pr}(-\Delta\theta_R)$ by 1-2% because of a slight increase in S_R.

Next, $Y_{pr}(-\Delta\theta S_R, \theta_R)$ in the case of decreasing S_R by OUVR with correlative θ_R change is illustrated in Figure 21 (a), as under 100% all over the country and under 90% in the eastern part of Hokkaido and the highlands of central Japan. In contrast, $Y_{pr}(+\Delta S_R, \theta_R)$ in case of increasing S_R is illustrated in Figure 21 (b), where areas of more than 105% extend from Hokkaido to the Pacific side of the Tohoku District.

The above mentioned Y_{pr} are for M_G fixed at the normal. In the next phase of research, M_G is independently changed by OUVR. When OUVR of θ_R(or S_R) and M_R occur simultaneously the joint probability of this event is 0.025; namely the return period of 39.5 years.

Y_{pr}, when both θ_R (with which S_R is correlated) and M_G are varied from the normal by OUVR is illustrated in Figure 22, where $Y_{pr}(-\Delta\theta_R, S_R, M_{G,r}\uparrow)$ shown on the left hand side, indicates the relative Y_p in case of decreasing θ_R and increasing M_G by OUVR, and $Y_{pr}(+\Delta\theta_R, S_R, M_{G,r}\downarrow)$ on the right hand side for increasing θ_R and decreasing M_G. The author assumes the former to be a cold temperature summer damage year which occurs once in 40 years and the latter in contrast a hot temperature summer year of occurring with similar frequency.

On looking at the cold temperature year, the areas of less than 90% Y_{pr} coincide with types A1 and A2, and the areas with more than 95% is restricted within type C5. On the other hand, during the hot temperature year, there exist areas with less than 100% in parts of types A3 and D, and in all of type B.

Table 5 Multipliers for estimating the variation range of the other variable.

Type	AT1 ($\times\Delta\theta_R$)	AT2 ($\times\Delta S_R$)
A 1	13.76	0.0101
A 2	14.27	0.0107
A 3	21.26	0.0116
B	16.67	0.0106
C 5	16.67	0.0106
C	−10.13	−0.0064
D	−7.20	−0.0072

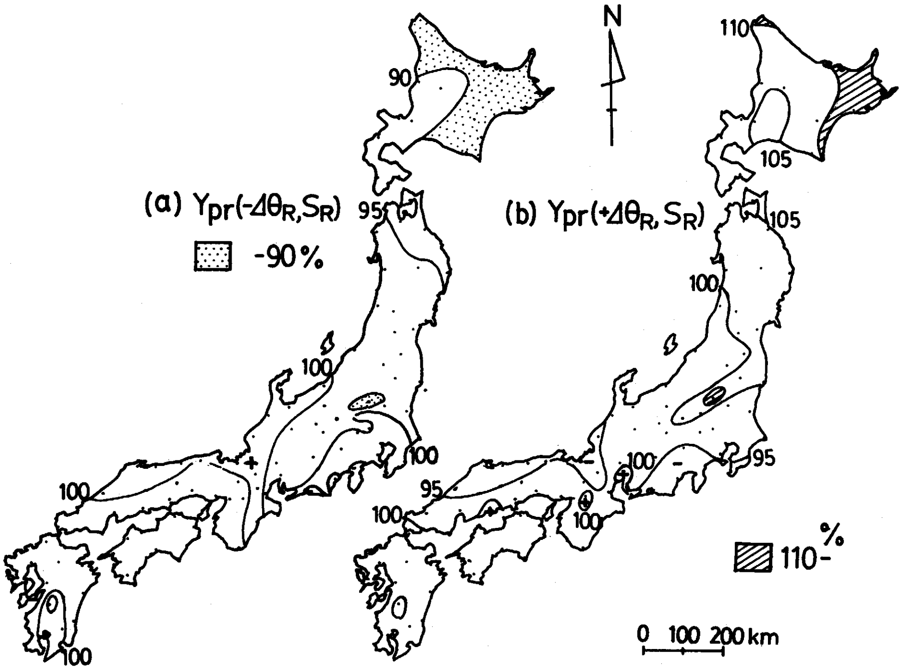

Fig. 20 Geographical distribution of (a) Y_{pr} $(-\Delta\theta_R,\ S_R)$ and (b) Y_{pr} $(+\Delta\gamma_R,\ S_R)$.

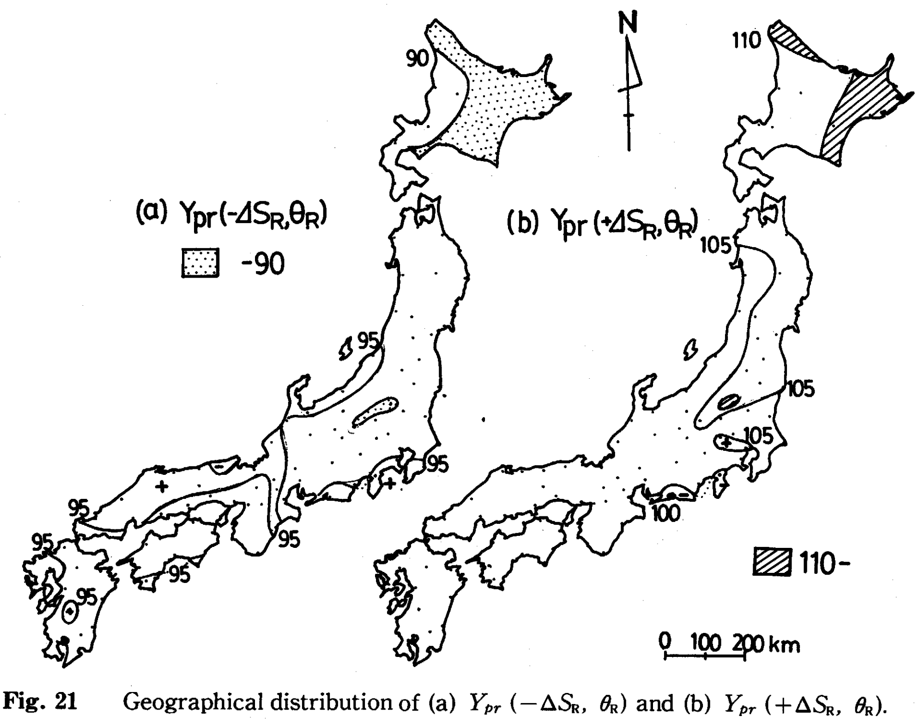

Fig. 21 Geographical distribution of (a) Y_{pr} $(-\Delta S_R,\ \theta_R)$ and (b) Y_{pr} $(+\Delta S_R,\ \theta_R)$.

Similarly, $Y_{pr}(-\Delta S_R, \theta_R, M_{G,r}\uparrow)$ and $Y_{pr}(+\Delta S_R, \theta_R, M_{G,r}\downarrow)$, when S_R (with which θ_R is correlated) and M_G are varied from the normal by OUVR, are illustrated in Figure 23. The former is assumed to represent the year of poor sunshine summer damage which occurs once in 40 years and the latter is assumed to represent a year over-abundant in sunshine which occurs with same frequency.

Figure 23(a) shows that for the poor sunshine year only the areas abundant in S_R such as the Akita plain to the Shonai plain, the Matsumoto basin and the Takayama basin maintain a 90% level of Y_{pr} and in other areas the Y_{pr} is less than 90%. In contrast, there are no areas with less than 100% $Y_{pr}(+\Delta S_R, \theta_R, M_{G,r}\downarrow)$ distribution in the abundant sunshine year, where the lowest level (less than 105%) is seen in some parts of type A3 which are abundant in sunshine conditions and in type B and type C5.

Comparison of Y_{pr} value estimated for return period of 6 and 39 years against Y_{pr} based on change of elements for corresponding return periods

The aim of this section is to compare some Y_{pr} values which will be estimated for some return periods due to long-range change of Y_p at the normal SHP with various Y_{pr} based on the elemental changes mentioned in the previous sections.

Return periods of Y_p concerning respective stations are illustrated in Figure 24, where the theoretical values (curves) and empirical values (symbols) systematically differ in increasing Y_p. The subjective return periods are 6 and 40 years, and results of comparison are represented in Table 6 for decreasing Y_{pr} and Table 7 for increasing Y_{pr}.

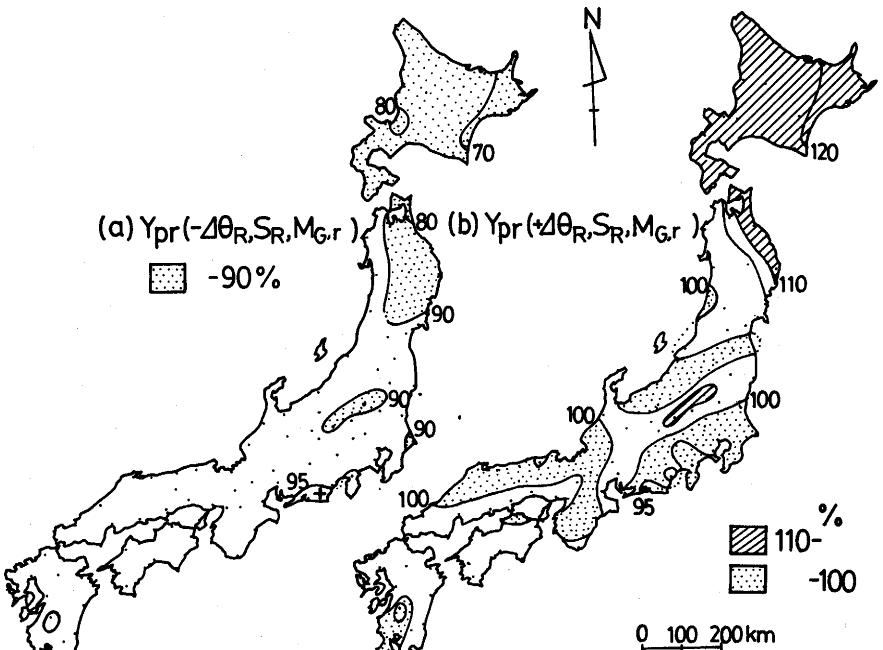

Fig. 22 Geographical distribution of (a) Y_{pr} $(-\theta_R, S_R, M_{G,r}\uparrow)$ and (b) Y_{pr} $(+\Delta\theta_R, S_R, M_{G,r}\downarrow)$.

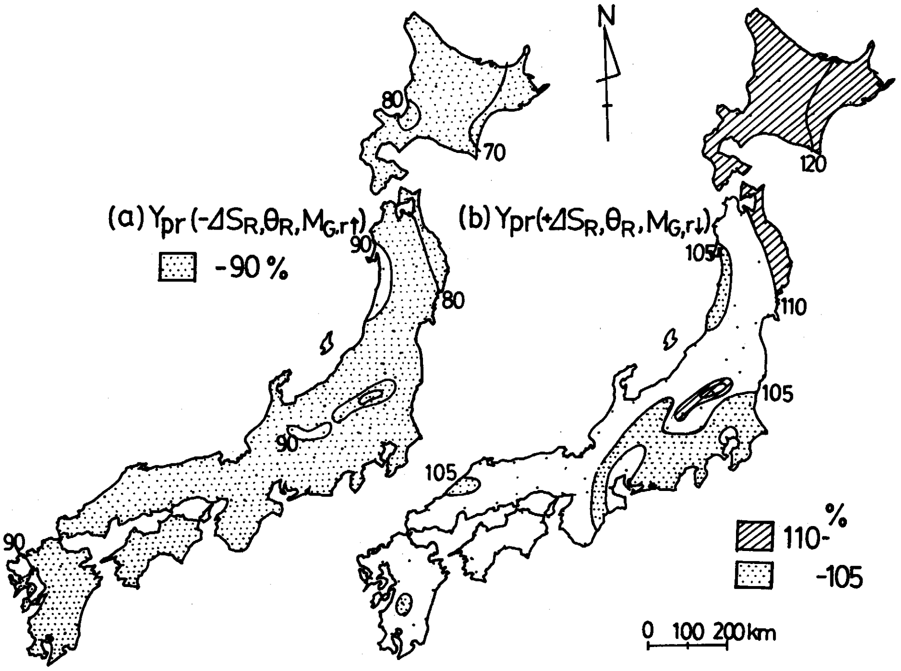

Fig. 23 Geographical distribution of (a) Y_{pr} $(-\Delta S_R,\ \theta_R,\ M_{Gr}\uparrow)$ and (b) Y_{pr} $(+\Delta S_R,\ \theta_R,\ M_{Gr}\downarrow)$.

The situation of decreasing Y_{pr} is represented in Table 6, where various Y_{pr} for return periods of 6 and 40 years against 6 stations standing for respective agro-climatic divisions are indicated. The Y_p value for return periods of 6.2 and 39.5 years, respectively, shown in the 4th and 7th columns of the table as $Y_{pr}(6.2)$ and $Y_{pr}(39.5)$, and theoretically estimated values. By comparing $Y_{pr}(-)$ with the various Y_{pr} in the table, their coincidence seems to be dependent on places.

In the case of $\tau=6.2$, the coincidence is as follows: in Asahikawa, $Y_{pr}(M_{G,r}\uparrow)$; in Matsumoto, $Y_{pr}(-\Delta S_R)$; in Ohita, $Y_{pr}(M_{G,r}\uparrow)$. In addition, the nearest Y_{pr} is $Y_{pr}(-\Delta S_R,\theta_R)$ in Morioka; $Y_{pr}(-\Delta S_R)$ in Niigata, $Y_{pr}(-\Delta S_R)$; and $Y_{pr}(-\Delta S_R)$ and $Y_{pr}(M_{G,r}\uparrow)$ in Saga.

In the case of $\tau=39.5$ years, $Y_{pr}(-)$ of Asahikawa and Morioka are less than $Y_{pr}(-\Delta S_R,\theta_R,M_{G,r}\uparrow)$ by 7%. The difference in the two kinds of Y_{pr} decreases to 4% in Matsumoto and to less than 2% in Niigata, Ohita and Saga. The regional difference between $Y_{pr}(39.5)$ and $Y_{pr}(-\Delta S_R,\theta_R,M_{G,r}\uparrow)$ seems to come from the regional difference in the independency between θ_R (or S_R) and M_G. In addition, it seems that there is a relatively intense correlation between S_R (or θ_R) and M_G in the following order; types A1, A2 and A3.

As to Table 7 of increasing Y_{pr} for $\tau=6.2$ years, the respective stations which come nearest to $Y_{pr}(-)$ are: in Asahikawa, $Y_{pr}(M_{G,r}\downarrow)$; in Morioka, $Y_{pr}(M_{G,r}\downarrow)$ and $Y_{pr}(+\Delta\theta_R,S_R)$; in Matsumoto, $Y_{pr}(M_{G,r}\downarrow)$ and $Y_{pr}(+\Delta\theta_R,S_R)$; in Niigata, $Y_{pr}(M_{G,r}\downarrow)$ and $Y_{pr}(+\Delta S_R,\theta_R)$; in Ohita, $Y_{pr}(+\Delta S_R)$ and $Y_{pr}(+\Delta S_R,\theta_R)$; and in Saga, $Y_{pr}(+\Delta S_R,\theta_R)$. On looking at $\tau=39.5$ the coincidence of $Y_{pr}(-)$ with $Y_{pr}(+\Delta S_R,\theta_R,M_{G,r}\downarrow)$ is clearly seen but for Morioka and Niigata $Y_{pr}(-)$ agrees with the mean of $Y_{pr}(+\Delta S_R, \theta_R, M_{G,r}\downarrow)$ and $Y_{pr}(+\Delta\theta_R, S_R, M_{G,r}\downarrow)$.

Conclusion

The variability of Y_p relative to the normal Y_{po} due to change in climatic elements approximately corresponding to the 6 year and the 40 year return period were calculated

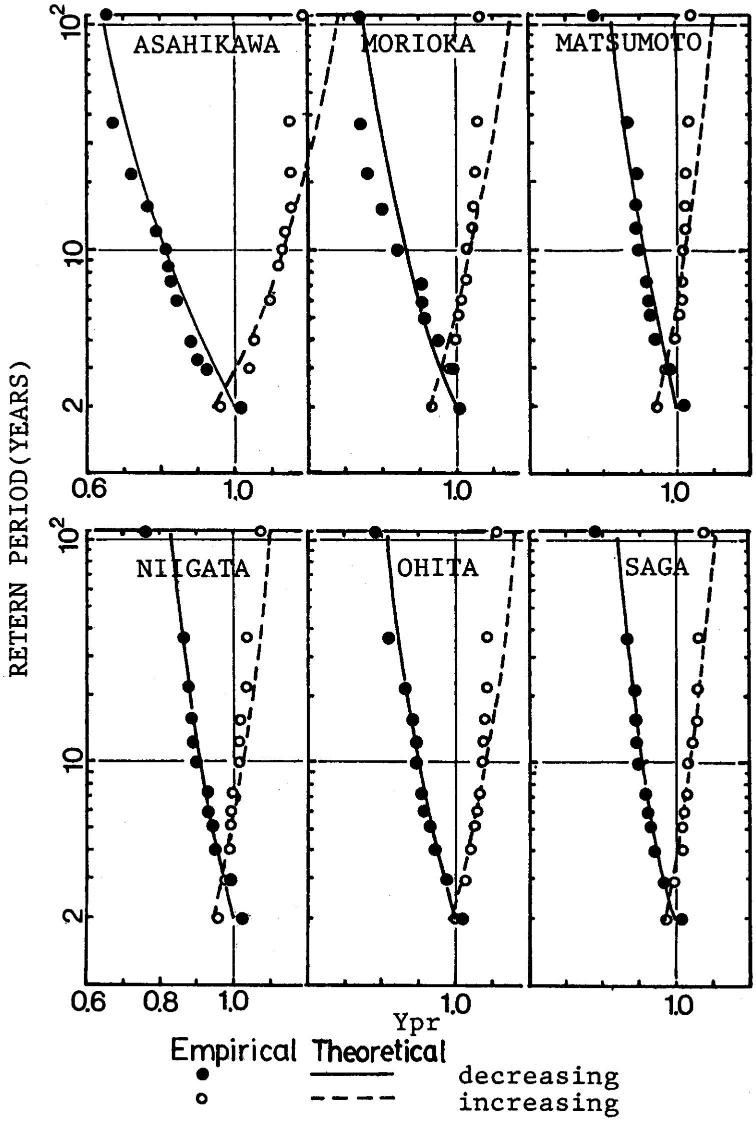

Fig. 24 Empirical and theoretical return periods of two kinds of Y_{pr}, decreasing Y_p relative to the mean Y_p and increasing Y_p relative to the normal Y_{po} at respective stations.

Table 6 Comparison of various Y_{pr} composed from change of climatic elements for two different return period of 6.2 and 39.5 years with the actual Y_{pr} for the same return periods in case of decreasing Y_{pr}.

Return period	6.2years						39.5years		
	Y_{pr},%						Y_{pr},%		
Stations (Type)	$-\Delta\theta_R$	$-\Delta S_R$	$M_{G,r}\uparrow$	—	$-\Delta\theta_R$, S_R	$-\Delta S_R$, θ_R	—	$-\Delta\theta_R$, S_R, $M_{G,r}$ $\uparrow$	$-\Delta S_R$, θ_R, $M_{G,r}$ $\uparrow$
Asahikawa (A 3)	94	92	85	85	92	90	70	78	77
Morioka (A 2)	97	93	95	90	95	92	80	89	87
Matsumoto (A 3)	99	92	96	92	96	93	85	93	89
Niigata (B)	101	93	90	92	99	95	86	90	86
Ohita (C)	96	94	92	92	98	94	86	91	87
Saga (D)	97	94	94	93	98	95	87	93	89

Table 7 Same as Table 6 but for in case of increasing Y_{pr}.

Return period	6.2years						39.5years		
	Y_{pr},%						Y_{pr}, %		
Stations (Type)	$+\Delta\theta_R$	$+\Delta S_R$	$M_{G,r}\downarrow$	—	$+\Delta\theta_R$, S_R	$+\Delta S_R$, θ_R	—	$+\Delta\theta_R$, $S_R.R_{G,r}$ $\downarrow$	$+\Delta S_R$, $\theta_R.M_{G,r}$ $\downarrow$
Asahikawa (A 3)	102	106	108	109	105	107	116	114	116
Morioka (A 2)	100	105	102	102	102	105	106	104	108
Matsumoto (A 3)	97	105	100	100	100	104	103	100	104
Niigata (B)	95	105	103	99	97	103	104	100	106
Ohita (C)	100	104	103	106	98	104	108	102	107
Saga (D)	99	104	102	102	98	104	106	100	106

for 99 meteorological stations and geographical distributions of them were illustrated in Figures 15, 16, 20 and 21 for the 6 year return period, and Figures 22 and 23 for the 40 year return period.

The effect of decreasing Y_p is most remarkable when M_G is increasing, except for types A2 and A3, where the decrease in S_R is most influential. However, by considering the correlation between θ_R and S_R, the effect of decreasing S_R and correlated θ_R is similar to the increasing of M_G. Climatic conditions before heading and the ripening period have been defined to equally affect climatic productivity in Y_p (refer to Sugihara and Hanyu, 1980).

In contrast, the effect of increasing Y_p is most remarkable when S_R is increased, except for type A1, where a decrease in M_G is most effective.

The correlation between θ_R and S_R depended on the agro-climatic divisions. In types A1, A2, A3 and B, the correlation coefficients were positive at around 0.4(**), but in types C and D, they were negative(*). This is due to the normal SHP being located in the mid-summer in the former divisions and located in the Shurin season in the latter divisions. The positive correlation between them in mid-summer is profitable.

The negative correlation between them in the Shurin season was explained by the example of Miyazaki (Figure 18). The late autumn cool air mass causes low air temperature and abundant sunshine.

Thus, the seasonal progression of the warm period is closely related to paddy cultivation, and the relation was represented in Figure 19, where the relationship between the actual mean heading period and the normal SHP were shown. At the stations where SHP is near to the height of the Shurin season the actual heading period is advanced by more than 15 days.

The decreased Y_p relative to the normal Y_{po} for the 40 year return period, was illustrated in the two cases of cold temperature summers (Figure 22(a)) and poor sunshine (Figure 23(a)), and judging from Table 8 the actual Y_{pr} (to the mean Y_p) for the 40 year return period is more similar to the latter. In addition, the Y_{pr} value should be smaller as the division is colder in types A1, A2, and A3, since the dependency on M_G and S_R (or θ_R) became less.

In contrast, in the case of increasing Y_p, Table 7 shows that the relative value of actual Y_{po} to the normal Y_{po} for the 40 year return period is most similar to the relative Y_p increase in the case of abundant sunshine (Figure 23 (b)).

Thus, geographical distribution of the relative Y_p variation based on the combined climatic variation possibly represents possible deviation from the normal in the climatic productivity for the return period of 40 years.

6. Conclusion

The summary of this present study is as follows:

(1) Agro-climatic division based on two kinds of Y_p variational patterns, one due to heading periods shifts and the other due to normal mean air temperatures changes was established, and was divided into 7 divisions (Figure 6). By comparison of the agro-

climatic divisions with the retionality based on Y_p yearly variation the 2 agreed in 75% of all regions (Figure 11).

(2) The long-term changes of stations representing 6 of the 7 agro-climatic divisions (excepting type C5) (Figure 12), clearly indicated the maximum and minimum values affecting substantially in the production of paddy rice at the stations in Asahikawa (type A1), Morioka (type A2) and Saga (type D) within the subject period (1926-1980). The maximum varience coefficient of Y_{po} generally appears at the minimum period of Y_{po}, and the maximum percentage of each station is as follows: Asahikawa, 20%, Morioka, 13%; Matsumoto, 5%; Niigata, 7%; Ohita, 7% and Saga, 8%.

(3) The correlation between Y_{po} and relative yields (Y_i) was summarized in Table 3, where the best correlations were found for the period before 1946. Technical factors exert a steady relative effect in keeping up the yield level after 1947 but paddy rice production before 1946 was strongly affected by natural surroundings (climatic productivity, *etc.*).

(4) Geographical distribution of relative Y_p (Y_{pr}) obtained from combining change in climatic elements for a 6 year return period (potential OUVR from the normal) were illustrated in Figures 15 and 16. By considering the correlation between θ_R and S_R in respective regions (Figure 17), the Y_{pr} obtained for the 6 year return period change of S_R and θ_R (Figures 20 and 21) is similar to the most effective Y_{pr} change in case of M_G(Y_{pr} ($M_{G,r}$)) in northern Japan.

(5) The Y_{pr} change for a return period 40 years were illustrated (Figures 22 and 23), and Y_{pr} for the same return period obtained by empirical and theoretical method (Figure 24) were compared with Y_{pr} composed of change in climatic elements (Tables 6 and 7). Geographical distribution of relative Y_p variation (Figure 23) based on the combined variation of climatic factors (S_R and M_G varid by OUVR and θ_R regarded as a dependant variable) represents a possible deviation in the climatic productivity from the normal for the return period of 40 years.

Remaining problems and subjects for climatic productivity in future are as follows:

(1) Limit of Y_p as prediction model

Y_p was not essentially represented for the purpose of a prediction model but for the purpose of estimation of climatic productivity of paddy rice in Japan. It estimates possible maximum yield of paddy rice under the cultivating technical level of routine crop situation tests (during the period 1973-77), and technical level means a mozaic structure of culture for the various varieties with various best techniques under a wide range of climatic conditions; namely from type A1 to type D.

However, since Y_p seemed adaptable for cold resistant and high-yielding varieties, Y_p was useful for the prediction of yield *etc.* in northern Japan. In other regions, Y_p may enable us to obtain effective prediction, provided parameterization of θ_o.

In the future, development of Y_p for respective varieties and each agro-climatic division including re-examiation of M_G will introduce fruitful results in practical field of paddy rice cultivation.

(2) Limit to Y_p applicaltion

In evaluating the climatic productivity of paddy rice in Japan, complete irrigation facilities and abundant precipitation enabled neglection of precipitation as a subjective climatic factor. In tropical Asia, including monsoon Asia, paddy fields without irrigation facilities are estimated at over 80% (Osada, 1975), and precipitation is a limiting factor in those areas (Maruyama, 1967).

The index Y_p was obtained for "japonica" under crop situation test cultivation conditions in Japan, and evaluation of climatic productivity in terms of Y_p should be confined to east Asia, European countries and the West Coast of the USA, where varieties grown are similar to "japonica."

In the future, the work of clarifying global climatic productivity of paddy rice inclusive of the tropics should be attempted making reference to the global distribution of net photosynthesis work done by Chang (1970).

(3) Reconstruction of climatic productivity in historical period

As shown in Summary (3), since the correlation between Y_p and yield are better in the past than at present, the author has already attempted (Sugihara, 1982) to develop this theme of reconstruction in northen Japan during the *Tenmei* and *Tempo* periods in *Edo* era.

In the future, further reconstruction in other regions can possibly be attempted with further research on climatic productivity itself (such as (1), (2)).

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(*in Japanese, **in Japanese with Engrish abstract)

Appendix

Objective Stations of This Study

(1st) 26 crop situation test stations:----------------------

a. Nagayama	b. Fujisaka	c. Iwate	d. Miyagi
e. Akita	f. Yamagata	g. Fukushima	h. Niigata
i. Ishikawa	j. Mito	k. Chiba	l. Utsunomiya
m. Nagano	n. Gifu	o. Anjyo	p. Mie
q. Azuchi	r. Tottori	s. Izumo	t. Okayama
u. Hiroshima	v. Yamaguchi	w. Bushozan	x. Saga
y. Kumamoto	z. Miyazaki		

(2nd) 36 main paddy regions:------(Number)-------------------

(3rd) 99 stations throughout Japan----Number----------------

.1 Wakkanai	(26)Matsumoto	51 Shimonoseki	(76)Hachinohe
.2 Abashiri	(27)Kumagaya	(52)Tokushima	77 Shinjo
(3) Asahikawa	28 Kofu	53 Matsuyama	78 Ishinomaki
.4 Nemuro	29 Tokyo	54 Iizuka	79 Shirakawa
.5 Otaru	(30)Choshi	(55)Fukuoka	80 Nikko
(6) Sapporo	(31)Matsue	(56)Kochi	81 Nagano
(7) Obihiro	(32)Yonago	57 Shionomisaki	82 Karuizawa
.8 Hakodate	33 Tottori	58 Hita	83 Kanazawa
(9) Aomori	34 Maizuru	59 Sasebo	84 Fukui
(10)Akita	35 Yokohama	(60)Saga	85 Suwa
(11)Morioka	(36)Hikone	(61)Ohita	86 Chichibu
.12 Miyako	37 Gifu	62 Murotomisaki	87 Iida
(13)Sakata	(38)Nagoya	(63)Kumamoto	88 Toyooka
(14)Sendai	39 Katsuura	64 Nagasaki	89 Himeji
(15)Yamagata	40 Kyoto	65 Nobeoka	90 Nara
(16)Niigata	(41)Shizuoka	66 Hitoyoshi	91 Ueno
.17 Fukushima	42 Hamada	(67)Miyazaki	92 Hamamatsu
(18)Wakamatsu	(43)Okayama	(68)Miyakonojo	93 Fukuyama
.19 Takada	44 Kobe	(69)Kagoshima	94 Owase
(20)Onahama	45 Osaka	70 Rumoi	95 Uwajima
(21)Toyama	(46)Tsu	71 Kushiro	96 Sukumo
.22 Utsunomiya	47 Hagi	72 Hiroo	97 Tsuyama
(23)Maebashi	48 Hiroshima	73 Suttsu	98 Mishima
.24 Mito	(49)Takamatsu	74 Mutsu	99 Urakawa
.25 Takayama	(50)Wakayama	75 Fukaura